REVIEWING THE HYDROGEN FUEL AND FREEDOMCAR INITIATIVES

HEARING

BEFORE THE

COMMITTEE ON SCIENCE
HOUSE OF REPRESENTATIVES

ONE HUNDRED EIGHTH CONGRESS

SECOND SESSION

MARCH 3, 2004

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March 3, 2004

REVIEWING THE HYDROGEN FUEL AND FREEDOMCAR INITIATIVES

WEDNESDAY, MARCH 3, 2004

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE,
Washington, DC.

The Committee met, pursuant to call, at 2:28 p.m., in Room 2318 of the Rayburn House Office Building, Hon. Sherwood L. Boehlert (Chairman of the Committee) presiding.

COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

"Reviewing the Hydrogen Fuel and FreedomCAR Initiatives"

Wednesday, March 3, 2004
2:00 pm
2318 Rayburn House Office Building

Witness List

David Garman
Assistant Secretary
Energy Efficiency and Renewable Energy
Department of Energy

Dr. Michael Ramage
Chair
National Academy of Sciences Committee on
Alternatives and Strategies for Future Hydrogen Production and Use

Dr. Peter Eisenberger
Chair
American Physical Society
Panel on Public Affairs - Energy Subcommittee

HEARING CHARTER

COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

Reviewing the Hydrogen Fuel and FreedomCAR Initiatives

WEDNESDAY, MARCH 3, 2004
2:00 P.M.–4:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

1. Purpose

On Wednesday, March 3, 2004, the U.S. House of Representatives' Committee on Science will hold a hearing to examine the Department of Energy's (DOE) Hydrogen Fuel and FreedomCAR initiatives. Specifically, the hearing will focus on two recent reports from the National Academy of Sciences (NAS) and the American Physical Society (APS) on DOE's hydrogen initiatives, and the Administration's response to the recommendations from the reports. The hydrogen program is one of the President's primary energy initiatives, and the two reports recommend changes to the program.

2. Witnesses

Mr. David Garman is the Assistant Secretary of Energy Efficiency and Renewable Energy at the Department of Energy. Prior to joining the Department, Mr. Garman served as Chief of Staff to Alaska Senator Frank Murkowski and has served on the professional staff of the Senate Energy and Natural Resources Committee and the Senate Select Committee on Intelligence.

Dr. Michael Ramage is the Chair of the National Academy of Sciences' (NAS), Committee on Alternatives and Strategies for Future Hydrogen Production and Use. Dr. Ramage is a retired executive vice president at ExxonMobil Research and Engineering Company.

Dr. Peter Eisenberger is the Chair of the American Physical Society's (APS) Panel on Public Affairs Energy Subcommittee. Dr. Eisenberger is currently a Professor of Earth and Environmental Sciences at Columbia University, and has extensive academic and corporate research experience at Harvard, Stanford, Princeton, Exxon, and Bell Laboratories.

3. Overarching Questions

The hearing will address the following overarching questions:

- Are the Hydrogen Fuel and FreedomCAR initiatives on track to provide a viable alternative to petroleum as a transportation fuel?
- Are the goals of the Hydrogen Fuel and FreedomCAR initiatives appropriate and realistic? Are the initiatives designed to meet their goals?
- What are the most important recommendations from the NAS and APS reports? How is the Department responding to the recommendations?
- Will technology research alone lead to a transition to hydrogen, or will it be necessary to apply policy tools? How should a research and development effort take these policy choices into account?

4. Overview

- In his 2003 State of the Union speech, President Bush announced the creation of a new Hydrogen Fuel Initiative, which built on the FreedomCAR initiative announced in 2002. Together, the initiatives aim to provide the technology for a hydrogen-based transportation economy, including production of hydrogen, transportation and distribution of hydrogen, and the vehicles that will use the hydrogen. Fuel cell cars running on hydrogen would emit only water vapor and, if domestic energy sources were used, would not be dependent on foreign fuels.
- The recent reports from the American Physical Society (APS) and the National Academy of Sciences (NAS) both recommend changes to the hydrogen

initiatives, particularly arguing for a greater emphasis on basic, exploratory research because of the significant, perhaps insurmountable, technical barriers that must be overcome. The APS report strongly cautions DOE against premature demonstration projects, saying such projects could repeat the government's unhappy experience with the synthetic fuels programs of the 1970s.

- The NAS study describes DOE's near-term milestones for fuel cell vehicles as "unrealistically aggressive." Both reports note that it will require technical breakthroughs—not just incremental improvements—to meet the goals of the overall hydrogen initiative. For example, the APS study states, "No material exists today that can be used to construct a hydrogen fuel tank that can meet the consumer benchmarks."
- The NAS study finds that in the DOE hydrogen program plan, the "priorities are unclear." The NAS study calls for "increased emphasis" on fuel cell vehicle development, distributed hydrogen generation, infrastructure analysis, carbon sequestration and carbon dioxide-free energy technologies.
- The NAS report notes that DOE needs to think about policy questions as it develops its research and development (R&D) agenda: "Significant industry investments in advance of market forces will not be made unless government creates a business environment that reflects societal priorities with respect to greenhouse gas emissions and oil imports.. . .The DOE should estimate what levels of investment over time are required—and in which program and project areas—in order to achieve a significant reduction in carbon dioxide emissions from passenger vehicles by mid-century."
- While the President's fiscal year 2005 (FY05) budget request includes additional funding for hydrogen R&D, it provides the money for hydrogen research by making cuts in other energy efficiency and renewable energy R&D programs. The APS report specifically argues against such an approach, and the NAS report notes that research on other aspects of renewable energy may be necessary for a successful transition to a hydrogen economy.
- The APS report recommends that DOE continue research into bridge technologies—such as gasoline or diesel hybrids and hydrogen-fueled internal combustion engines—that could provide benefits if the commercialization of fuel cell vehicles is delayed.

5. Background

Report Recommendations

NAS report recommendations summary

The NAS report raises "four pivotal questions" about the transition to a hydrogen economy:

- When will vehicular fuel cells achieve the durability, efficiency, cost, and performance needed to gain a meaningful share of the automotive market? The future demand for hydrogen depends on the answer.
- Can carbon be captured and sequestered in a manner that provides adequate environmental protection but allows hydrogen to remain cost-competitive? The entire future of carbonaceous fuels in a hydrogen economy may depend on the answer.
- Can vehicular hydrogen storage systems be developed that offer cost and safety equivalent to that of fuels in use today? The future of transportation use depends on the answer.
- Can an economic transition to an entirely new energy infrastructure, both the supply and the demand side, be achieved in the face of competition from the accustomed benefits of the current infrastructure? The future of the hydrogen economy depends on the answer.[1]

The report examines possible answers to the questions and recommends changes to the DOE hydrogen R&D program. The study concludes that, even under the most optimistic scenario, "[T]he impacts on oil imports and CO_2 emissions are likely to be minor during the next 25 years." The report goes on to add, "[T]hereafter, if R&D is successful and large investments are made in hydrogen and fuel cells, the impact on the U.S. energy system could be great."

The report's recommendations are summarized below.

[1] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.* NAS pre-publication copy, pp. 2–13.

Major NAS Recommendations:

- *Systems Analysis*—DOE should undertake more systems analysis to better understand the challenges, progress, and potential benefits of making the transition to a hydrogen economy.
- *Fuel Cell Vehicle Technology*—DOE should increase funding for fundamental research and development of fuel cells focusing on on-board storage systems, fuel cell costs, and durability.
- *Infrastructure*—DOE should provide "greater emphasis and support" to research, especially exploratory research, related to the creation of a hydrogen infrastructure. DOE should "create better linkages between its seemingly disconnected programs in large-scale and small-scale hydrogen production."
- *Infrastructure*—DOE should accelerate work on codes and standards, particularly addressing overlapping regulation at the municipal, State, and federal levels.
- *Transition*—DOE should strengthen its policy analysis to better understand what government actions will be needed to bring about a hydrogen economy.
- *Transition*—DOE should increase investments in research and development related to distributed hydrogen production.
- *Safety*—DOE should make changes to hydrogen safety programs, including developing safety policy goals with stakeholders.
- *Carbon Dioxide-Free Hydrogen*—DOE should increase emphasis on electrolyzer development with a target of $125 per kilowatt with 70 percent efficiency. In parallel, DOE should set more aggressive electricity cost targets for unsubsidized nuclear and renewable energy that might be used to produce hydrogen.
- *Carbon Capture and Storage*—DOE should link its hydrogen programs more closely with its programs on carbon sequestration (which are managed by Fossil Energy).
- *RDD Plan*—DOE should set clearer priorities for hydrogen R&D and better integrate related programs spread among several DOE offices. Congress should stop earmarking funds for hydrogen R&D.
- *RDD Plan*—DOE should shift work away from development and toward exploratory work and should establish interdisciplinary energy research centers at universities.
- *Framework*—DOE should give greater emphasis to fuel cell vehicle development, distributed hydrogen generation, infrastructure analysis, carbon sequestration and FutureGen, and carbon dioxide-free energy technologies.

APS report recommendations summary

The APS recommendations are generally consistent with those of NAS. The primary recommendation of the APS report is that DOE should significantly increase the funding for basic research in the hydrogen initiative, while reducing the funding for demonstrations. The report outlines the various technical barriers facing each stage of hydrogen usage, and the fundamental research breakthroughs that are needed to make the initiative a success. APS concludes that large-scale demonstrations are generally premature because so many technological hurdles still must be cleared.

The APS report also recommends that the Administration increase funding for "bridge" technologies—such as hydrogen internal combustion engines and gasoline and diesel hybrid vehicles—that would provide benefits sooner than hydrogen fuel cell vehicles, particularly if technical barriers slow the market penetration of the fuel cell vehicles. The APS report also argues that the hydrogen initiatives should not displace other efficiency and renewable energy research if the goals of the initiative are to be met. Renewable energy generation, APS argues, is crucial to supplying clean, domestic energy for hydrogen production.

Challenges

What are the technical challenges?

Major advances are needed across a wide range of technologies if hydrogen is to be affordable, safe, cleanly produced, and readily distributed. The production, storage and use of hydrogen all present significant challenges.

Hydrogen can be produced from a variety of sources, including coal and natural gas. But one goal of using hydrogen is to reduce emissions of carbon dioxide. If hydrogen is to be produced without emissions of carbon dioxide, then the technology to capture and store carbon dioxide (known as carbon sequestration) must improve significantly. The other main goal of using hydrogen is to reduce the use of imported energy. Today most hydrogen is produced from natural gas, but in order to supply the entire transportation sector significant imports of natural gas would be required. Other possible means of producing hydrogen are inherently cleaner than coal, but are far from affordable with existing technology. For example, the APS estimates that hydrogen produced through electrolysis is currently four to ten times more expensive than gasoline.

Another major hurdle is finding ways to store hydrogen, particularly on board a vehicle. APS believes "a new material must be discovered" to develop an affordable hydrogen fuel tank.

The NAS estimates that fuel cells themselves will need a ten- to twenty-fold improvement before fuel cell vehicles become competitive with conventional technology. Today's fuel cells also wear out quickly, and are therefore far short of the durability that would be required to compete with a gasoline engine. Finally, if hydrogen is going to be produced on a large-scale, dramatic improvements in pipeline and tanker technology are required to permit the efficient and safe transportation and distribution of hydrogen. Small-scale distributed production also needs improvement, and the NAS report recommends increased focus in that area because it may be the first to develop.

What are the non-technical challenges? (policy, regulatory, inertia, public awareness)

Even if the technology advances to a point at which it is competitive, the transition to a hydrogen economy will require an enormous investment to create a new infrastructure. Changes in regulation, training and public habits and attitudes will also be necessary. Estimates of the cost of creating a fueling infrastructure (replacing or altering gas stations) alone are in the hundreds of billions of dollars.

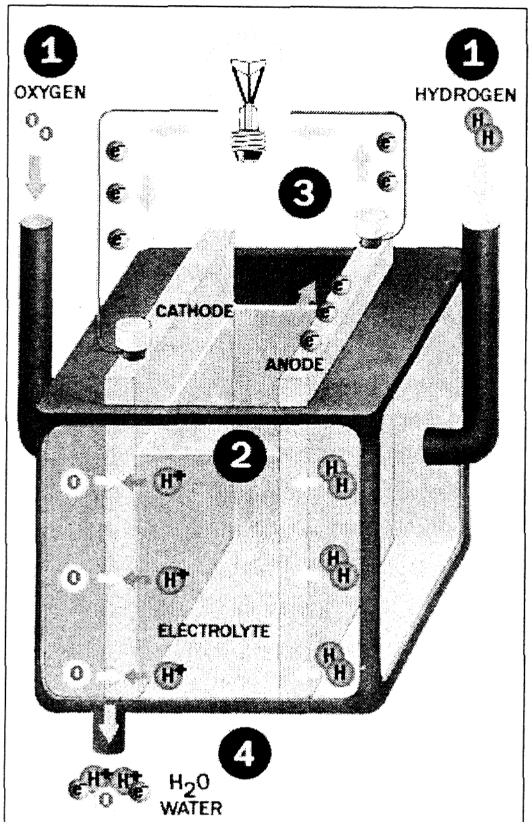
The transition also won't happen quickly. According to the NAS study, significant sales of hydrogen vehicles are unlikely before 2025 even under the most optimistic technology assumptions.

Technology

What is a Fuel Cell?

Central to the operation of the hydrogen-based economy is a device known as a fuel cell that would convert hydrogen fuels to electricity. In cars, these devices would be connected to electric motors that would provide the power now supplied by gasoline engines. A fuel cell produces electricity by means of an electrochemical reaction much like a battery. However, there is an important difference. Rather than using up the chemicals inside the cells, a fuel cell uses hydrogen fuel, and oxygen extracted from the air, to produce electricity. As long as hydrogen fuel and oxygen are fed into the fuel cell, it will continue to generate electric power.

Different types of fuel cells work with different electrochemical reactions. Currently most automakers are considering Proton Exchange Membrane (PEM) fuel cells for their vehicles.



1. Hydrogen gas is extracted from natural gas or other sources and permeates the anode. Oxygen from the air permeates the cathode.
2. Aided by a catalyst in the anode, electrons are stripped from the hydrogen. Hydrogen ions pass into the electrolyte.
3. Electrons cannot enter the electrolyte. They travel through an external circuit, producing electricity.
4. Electrons travel back to the cathode where they combine with hydrogen ions and oxygen to form water.

Source - DOE

Benefits of a Hydrogen-based Economy

A hydrogen-based economy could have two important benefits. First, hydrogen can be manufactured from a variety of sources, including natural gas, biofuels, petroleum, coal, and even by passing electricity through water (electrolysis). Depending on the choice of source, hydrogen could substantially reduce our dependence on foreign oil and natural gas.

Second, the consumption of hydrogen through fuel cells yields water as its only emission. Other considerations, such as the by-products of the hydrogen production process, will also be important in choosing the source of the hydrogen. For example, natural gas is the current feedstock for industrial hydrogen, but its production releases carbon dioxide; production from coal releases more carbon dioxide and other emissions; and production from water means that pollution may be created by the generation of electricity used in electrolysis. Production from solar electricity would mean no pollution in the generation process or in consumption, but is currently more expensive and less efficient than other methods.

Table 1. Current Federal Activities

Hydrogen Initiatives Budget ($ million)					
Department/Office	**2003 Actual***	**2004 Enacted****	**2005 Request**	**Dollar Change, 2004 to 2005**	**Percent Change, 2004 to 2005**
Energy / EERE Hydrogen Fuel	92	147	173	26	17
Energy / EERE FreedomCAR	152	155	169	14	9
Energy / Fossil Energy (coal)	2	5	16	11	227
Energy / Nuclear Energy	2	6	9	3	41
Energy / Basic Energy Sciences	0***	0***	29	29	-
Department of Transportation	0	0.6	0.8	0.3	50
TOTAL ******	**180**	**249**	**319**	**71**	**28**

* Reflects funding for baseline activities that the Hydrogen Fuel Initiative (HFI) augments and/or redirects. 2004 was the first year for the HFI, 2003 was the first year for FreedomCAR.

** Reflects rescissions, general reductions, and other adjustments included in relevant 2004 appropriations.

*** Base funding for hydrogen-related activities in Basic Energy Sciences was roughly $8 million in 2003 and 2004. These activities have been reoriented and expanded to support the goals of the President's HFI in 2005.

**** Columns do not add due to FreedomCAR and HFI funding overlaps and rounding.

Industry participation

Although exact numbers on industry involvement are proprietary, the major automobile companies have invested billions of dollars in R&D and demonstrations of fuel cell vehicles. General Motors alone had spent $1 billion as of June 2003, and estimated that its total investment by 2010 could triple.

Legislation

Language in the portion of the comprehensive Energy Bill (H.R. 6) produced by the Science Committee would authorize and guide the hydrogen initiative. The conference report on H.R. 6 is still pending in the Senate.

6. Questions to the Witnesses

The witnesses have been asked to address the National Academy of Sciences' (NAS) and American Physical Society's (APS) recent reports and recommendations on the hydrogen initiatives in their testimony, and in addition the following specific questions.

Mr. David Garman:

1. The NAS report describes the goals of the initiatives as "unrealistically aggressive" while the APS report highlights the significant "performance gaps" between current technology and the initiative milestones. Does the Department of Energy (DOE) plan to adjust the goals based on the comments of these reports? If not, how does DOE plan to respond?
2. Because of the significant technical challenges, both reports criticized the current mix of funding for hydrogen research, arguing that more emphasis should be placed on fundamental research as opposed to demonstrations. Please describe the hydrogen program's current demonstration and deployment efforts, and how each technology element's current costs and performance measure against the program goals. Does DOE plan to adjust the balance of funding to match the recommendations? If not, why?
3. The NAS report suggests that the research agenda should be developed with future policy decisions in mind. How did the Administration consider the impact of future policy decisions in the development of the research agenda for the hydrogen initiatives? Does DOE plan on increasing its policy analysis capabilities as recommended by the NAS?
4. What are the key criteria for deciding that a technology is ready for demonstration? Are there guidelines or rules of thumb, such as 120 percent of cost goals, or 85 percent of performance goals that indicate that a technology is ready for demonstration-scale activities?
5. Using the definitions in OMB Circular A–11, what is the proposed mix of funding in the FY05 budget request between basic research, applied research, development, demonstration, and deployment activities within the Hydrogen Fuel Initiative?

Dr. Michael Ramage:

1. Given the current state of hydrogen technology, what do you feel the federal funding balance should be between demonstration and research?
2. One of the recommendations included in the NAS report calls for an expanded policy analysis program at the Department of Energy. Please describe why the committee felt this was important, and give more detail as to what such a program might encompass.
3. In the penetration models included in the NAS study, the committee assumes that the technical goals will be met, even though they are deemed overly optimistic. What would be more realistic goals? How would that affect the penetration models? What would that imply for the delivery of public benefits such as environmental improvements and reduced oil dependence?
4. What are the key criteria for deciding that a technology is ready for demonstration? Are there guidelines or rules of thumb, such as reaching 120 percent of cost goals, or 85 percent of performance goals, that indicate that a technology is ready for demonstration-scale activities?
5. While the NAS report recommends shifting funding away from "bridge" technologies such as gasoline and diesel hybrids and hydrogen internal combustion engines, another recently released report from the American Physical Society (APS) encourages DOE to increase funding in these areas in light of their near-term benefits. How would you respond to the APS recommendation? What do you feel is the reason for the different opinions about federal investment in bridge technologies?

Dr. Peter Eisenberger:

1. One of the major themes of the APS report is the lack of funding for basic research. The report notes that the Department's request of $29 million in the Office of Science for fiscal year 2005 was a dramatic improvement, but says that the amount of basic research is still inadequate at 13 percent of the overall hydrogen funding. What do you feel the balance should be? How should it change over time?
2. What are the key criteria for deciding that a technology is ready for demonstration? Are there guidelines or rules of thumb, such as reaching 120 percent of cost goals, or 85 percent of performance goals, that indicate that a technology is ready for demonstration-scale activities?
3. While the APS report encourages DOE to increase funding to "bridge" technologies such as gasoline and diesel hybrids and hydrogen internal combus-

tion engines, another recently released report from the National Academy of Sciences (NAS) recommends shifting funds away from bridge technologies. How would you respond to the NAS recommendation? What do you feel is the reason for the different opinions about federal investment in bridge technologies?

Chairman BOEHLERT. The Committee will be in order. Now prior to our hearing, I must ask your patience while I complete one brief administrative matter. Specifically, I would like to ask the Committee for unanimous consent to discharge House Joint Resolution 57, expressing the sense of Congress that the Congress recognize the contributions of the seven *Columbia* astronauts by supporting the establishment of a *Columbia* Memorial Science Learning Center in Downey, California. I know that there is strong bipartisan support for this resolution, and I understand the support of the entire California delegation. Therefore, without objection, so ordered.

I want to welcome everyone here for this important hearing on one of the President's key initiatives. This hearing is important because what is at stake over the long-term is the security of our nation, the availability of resources for economic growth here and around the world, and the health of the environment, nationally and globally, not exactly minor issues. The President is to be congratulated for his foresight in proposing the Hydrogen Initiative. It will take at least a decade of focused effort to lay the foundation for a hydrogen economy.

The question before us today is not whether to have a hydrogen initiative, but how to make sure we get the most out of what we are spending on this program. If we think of the Hydrogen Initiative as a car, which I think is an appropriate analogy, then I would say that the President has bought us the car and the Secretary of Energy has turned the ignition key, but everyone is still learning how to drive and no one has mapped out a clear travel plan yet.

So we are at a critical juncture in the development of this initiative, and I am pleased that we will be able to get guidance today from two prestigious organizations: the National Academy of Sciences (NAS), and the American Physical Society (APS), represented here by two distinguished researchers. I found the recommendations in their two reports to be compelling, and I hope we will be able to hear some specifics today about exactly how the Department of Energy (DOE) is going to implement them. Clearly, this is a valuable program that could be better focused with greater emphasis on solving fundamental questions.

I am pleased that we have Secretary Garman back with us today, a good friend, one who has appeared here many, many times, to tell us how DOE intends to proceed. He is a leading light in the Department and a true believer in these technologies. And he has his work cut out for him with this initiative. I also want to thank Secretary Garman for appearing before us during a week in which he has already made a number of congressional appearances, but I am sure that as a former Senate staffer he feels he just can't spend too much time up here.

Before we hear from our witnesses, I want to highlight two points made in the reports I referred to earlier that go beyond the technical recommendations, points I have made in previous hearings on this subject. First, most reports acknowledge that there is no way to discuss the transition to a hydrogen economy or the research to get us there without dealing forthrightly with policy questions. No mysterious market force alone is going to produce a hydrogen economy. I would urge DOE again to make that acknowledgment itself and to plan accordingly. We can't, for example, have a sensible hydrogen R&D agenda without making some decisions about essential carbon sequestration, how that is going to be in a hydrogen economy. Personally, I think it has to be essential, but we need a decision by DOE. Second, both reports note that other work on energy efficiency and renewable energy is necessary for a hydrogen economy to be clean and affordable, and both reports are right.

So I think it is unfortunate that the Administration proposes to pay for hydrogen research by cutting the rest of Secretary Garman's programs. We have been told in the past that such triage would not occur, and it shouldn't.

Finally, let me say that I also agree with these reports when they point out that hydrogen is no panacea, especially in the short-term. Work on hydrogen should be not used an excuse—as an excuse to avoid steps we need to take now, steps like stricter CAFE standards, like promoting hybrid vehicles, like conducting R&D on interim solutions to our energy dependence and pollution problems.

Our focus at this hearing is on the Hydrogen Initiative itself. I hope we can reach some consensus today on how the research agenda can be reshaped to increase the likelihood that hydrogen can someday become the answer to our energy and environmental needs.

Mr. Gordon.

[The prepared statement of Chairman Boehlert follows:]

PREPARED STATEMENT OF CHAIRMAN SHERWOOD BOEHLERT

I want to welcome everyone here for this important hearing on one of the President's key initiatives. This hearing is important because what's at stake, over the long term, is the security of our nation, the availability of resources for economic growth here and around the world, and the health of the environment, nationally and globally. Not exactly minor issues.

The President is to be congratulated for his foresight in proposing the hydrogen initiative. It will take at least a decade of focused effort to lay the foundations for a hydrogen economy.

The question before us today is not whether to have a hydrogen initiative, but how to make sure we get the most out of what we're spending on this program. If we think of the hydrogen initiative as a car—an appropriate analogy—then I would say that the President has bought us the car and the Secretary of Energy has turned the ignition key, but everyone is still learning how to drive, and no one has mapped out a clear travel plan yet.

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But our focus at this hearing is on the hydrogen initiative itself. I hope we can reach some consensus today on how the research agenda can be reshaped to increase the likelihood that hydrogen can some day become the answer to our energy and environmental needs.

Mr. Gordon.

Mr. GORDON. Thank you, Mr. Chairman. I always enjoy listening to you, because I just agree with you so much on what you say. It is such a nice thing to have a sensible chairman. Thank you for giving me my opportunity also.

In my part of Tennessee, we have a special interest in hydrogen fuel vehicles in the form of Dr. Cliff Rickets at Middle Tennessee State University. For many years, Dr. Rickets has been working with alternative fuels and has built cars that run on everything from corn to cow manure. Since the late '80's, he has been working with hydrogen fuel engines. In fact, in 1991, he built a car that set the world land speed record for hydrogen at the Bonneville speed trials at the Great Salt Flats in Utah. The next year, his team went back and broke his own record, a record that has now stood for more than 10 years.

And in Tennessee, we come about our interests in hydrogen honestly and believe that in addition to going fast, we can also transition to a fuel that can be cleaner and reduce our need for imported oil. But we have to be sensible and smart about how we go about it, and that is the subject of this hearing. The importance of energy to society can not be overstated. Since prehistoric—or prehistory, the survival and the advancement of civilization has depended on the ability to secure energy resources. From the gathering of wood to the burning of fossil fuels to the fission of nuclear materials, our quest for energy has shaped the world, as we know it. The agricultural and industrial revolutions of the last two centuries would not have been possible had it not been for coal, oil, and natural gas.

However, finding alternatives to fossil fuels is imperative. We have known this for a generation yet no viable, cost-efficient alternative has emerged. Hydrogen has developed as a potential solution to our energy puzzle, but will it work? And furthermore, will it work within the timeline and technical goals laid out by the Administration's Hydrogen Initiative. With over two billion internal combustion engines in the world, a switch to a hydrogen-based economy is no easy task, and that is why I am pleased that we have these very informed officials with us today. And I look forward to hearing from you and taking us further down this path.

Thank you, Mr. Chairman.

Chairman BOEHLERT. Thank you very much, Mr. Gordon.

The Chair recognizes the distinguished Chair of the Subcommittee on Energy, Ms. Biggert.

Ms. BIGGERT. Thank you very much, Mr. Chairman. And thank you for calling this hearing and giving this committee another opportunity to get an update on the work underway at the Department of Energy as part of the President's Hydrogen Fuel and FreedomCAR Initiatives. I also want to thank the witnesses for being so generous with their time and for agreeing to share with us their insight and expertise on the topic of fuel cells and hydrogen.

I have a keen interest in both the fuel cell and Hydrogen Initiatives that President Bush announced in 2002 and 2003 respectively. As a matter of fact, in June of 2002, I chaired a field hearing in Naperville, Illinois to examine the potential of hydrogen fuel cell technology. My District is, of course, home to Argonne National Laboratory, which has a strong fuel cell R&D program. My District is also home to small businesses like H2Fuels and various auto parts suppliers, corporations like BP, and research organizations like the Gas Technology Institute. In short, I have the privilege to represent a region that has much to contribute to the continuing development of fuel cells and the hydrogen needed to fuel them.

As I have said many times before, I do not believe that affordable energy and a clean and safe environment are mutually exclusive. America has the ingenuity and the expertise to meet our nation's future energy demands and promote energy conservation. And we can do so in environmentally responsible ways that set a standard for the world. Most importantly, America now has the motivation, perhaps like no other time since the oil crisis of the '70's, to find newer and better ways to meet our energy needs.

Let us look at the facts. Our dependence on foreign oil sources is up almost—to almost 60 percent. Violence in the Middle East and the War Against Terrorism will continue to cause more volatility in gasoline prices that any of us will find acceptable. The bottom line is that the United States is home to only two percent of the world's supply of oil. It doesn't take a chemical engineer or a foreign policy expert to understand what that equals: continued dependency on increasingly uncertain sources.

There clearly are some compelling reasons to work toward our shared vision of a hydrogen economy. Today we will hear testimony about two recent reports, one prepared by the National Academy of Sciences, the other one by the American Physical Science Society, that raises questions about our progress in making that vision a reality.

We are talking about a tremendously challenging endeavor. It will take us many years to reach our goal. It only makes sense that we will need to make a few mid-course corrections along the way, that is why we should be asking are the goals we initially set still the right goals. If so, we must next ask are we working to meet our goals in the best way that we can. For instance, many fundamental technical obstacles remain in hydrogen production, transport, and storage, not to mention the technical challenges that we must address before fuel cell vehicles become a common future of American life.

To overcome these obstacles, the Federal Government must maintain a strong commitment to basic research. If the road we are on turns out to be a dead end, we should have an alternative route already mapped out. That is the reason a diverse portfolio of basic research is so important to long-term technology initiatives like the ones we are discussing today. Our job at this hearing is to look at what we have learned in the first year or two of our efforts and to gain insight from NAS and APS reports. Both recommend greater emphasis on basic research, which I think is the right course of action, and both point out that a great deal of work lies ahead.

I am confident that DOE is up to the task, and with the constructive input of groups like NAS and APS, we will move the Nation ever closer to realizing the promise and potential of fuel cells and hydrogen.

Thank you very much, Mr. Chairman, and I yield back.

[The prepared statement of Mrs. Biggert follows:]

PREPARED STATEMENT OF REPRESENTATIVE JUDY BIGGERT

Thank you, Chairman Boehlert, for calling this hearing and giving this committee another opportunity to get an update on the work underway at the Department of Energy as part of the President's Hydrogen Fuel and FreedomCAR initiatives. I also want to thank the witnesses for being so generous with their time, and for agreeing to share with us their insight and expertise on the topics of fuel cells and hydrogen.

I have a keen interest in both the fuel cell and hydrogen initiatives that the President announced in 2002 and 2003 respectively. As a matter of fact, in June 2002, I chaired a field hearing in Naperville, Illinois to examine the potential of hydrogen fuel cell technology. My district is, of course, home to Argonne National Laboratory, which has a strong fuel cell R&D program. My district also is home to small businesses like H2Fuels and various auto parts suppliers, corporations like BP, and research organizations like the Gas Technology Institute. In short, I have the privilege to represent a region that has much to contribute to the continued development of fuel cells and the hydrogen needed to fuel them.

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Our job at this hearing is to look at what we've learned in the first year or two of our efforts, and to gain insight from the NAS and APS reports. Both recommend greater emphasis on basic research, which I think is the right course of action, and both point out that a great deal of work lies ahead. I am confident that the DOE is up to the task and, with the constructive input of groups like the NAS and APS, will move the Nation ever-closer to realizing the promise and potential of fuel cells and hydrogen.

Thank you.

Chairman BOEHLERT. Thank you very much, Ms. Biggert.

[The prepared statement by Mr. Burgess follows:]

PREPARED STATEMENT OF REPRESENTATIVE MICHAEL C. BURGESS

Thank you Mr. Chairman, and thank you for having this hearing.

I believe that energy independence is a matter of national security. The United States is especially vulnerable to international price fluctuations since we import nearly 60 percent of the oil we consume daily from foreign sources, and this number is expected to increase to 75 percent by 2010. Most of this oil comes from the Middle East and politically unstable nations such as Algeria, Nigeria and Venezuela. When we met one year ago, to discuss this very issue, gas prices were soaring as a result of a two-month strike in Venezuela. This is merely one example of how international situations can affect the United States.

Our economy depends on access to steady, affordable and reliable domestic energy supply; it is a matter of national security to have the United States be self-sufficient when it comes to our energy needs. To ensure America's energy independence, I believe that we need to implement a long-term, comprehensive energy policy. Furthermore, one component of this national energy policy must be alternative energy research and development.

President Bush, during his 2001 State-of-the-Union Address, proposed a bold FreedomCAR and Hydrogen Fuel Initiative. The goal of this new FreedomCAR program is to make hydrogen fuel cell technology a viable, affordable and convenient technology that we can use to power our automobiles. There are many benefits, including a cleaner environment, greater energy independence, and the possibility that research can spur further technological innovation.

As a member of both the Science and Transportation and Infrastructure Committees, I recognize the unique challenges that we face as we discuss the possibility of converting into a hydrogen-fueled economy. We must discuss the appropriate role for the Federal Government in this process and examine our focus on FreedomCAR and hydrogen-based infrastructure, but we must do so within the context of a comprehensive energy policy. A comprehensive energy policy will help ensure that the United States can achieve energy independence. In addition, we must also take seriously our responsibility to ensure that taxpayer dollars are spent wisely and must keep this in mind as we discuss the President's Hydrogen Initiative.

So, again, Mr. Chairman, I thank you for this hearing in which we can address some our concerns.

[The prepared statement by Mr. Costello follows:]

PREPARED STATEMENT OF REPRESENTATIVE JERRY F. COSTELLO

Good afternoon. I want to thank the witnesses for appearing before our committee to discuss the President's Hydrogen Initiative and two recently released reports from the National Academy of Sciences (NAS) and the American Physical Society (APS) on DOE's Hydrogen Initiative. The hydrogen program is one of the President's primary energy initiatives, and the two reports recommend changes to the program.

On February 27, 2003, the President announced the FutureGen project. This project is a $1 billion government/industry partnership to design, build, and operate a nearly emission-free, coal-fired electric and hydrogen production plant. The prototype plant will serve as a large-scale engineering laboratory for testing and will expand the options for producing hydrogen from coal and capturing CO_2.

I have led the effort to locate FutureGen in Illinois, including leading a bipartisan effort in the House to secure funding for the project. Further, last July, I hosted a roundtable discussion regarding FutureGen and what it means for Illinois with Governor Blagojevich, U.S. Senators Durbin and Fitzgerald, and U.S. Congressman John Shimkus. Dr. C. Lowell Miller, Director of the Office of Coal Fuels and Industrial Systems at the Department of Energy, made a presentation on the specifics of the project.

I believe that Southern Illinois is the perfect place to locate the new plant. The region is rich in high-sulfur coal reserves and the Coal Center at Southern Illinois University Carbondale is located there. In addition, the geology of the region is well suited to the carbon-trapping technology to be developed. Illinois is home to oil and gas reserves and deep saline aquifers that can permanently sequester carbon dioxide.

I have been tracking this issue closely since its inception and I am anxious to see the Department's program plan. This Administration has touted FutureGen as one of the most important climate change technologies at our disposal and heightened its international visibility to extraordinary levels. If it is as important as the Administration has said, and I believe it is, I hope that the Administration will take a hard look at the program plan, your posture toward industry, and seek to move on a path forward that is technically, financially, and politically viable. We all want to make this work, but the program will go nowhere without a sound program plan upon which everyone agrees.

Finally, I was pleased to see the NAS and the APS both placed the FutureGen project as a high priority task for advancing development of hydrogen from coal.

I again thank the witnesses for being with us today and providing testimony to our committee.

[The prepared statement by Ms. Johnson follows:]

PREPARED STATEMENT OF REPRESENTATIVE EDDIE BERNICE JOHNSON

Mr. Chair, I thank you for calling this very important hearing. Our honored witnesses, I thank you for appearing here today to discuss such a vital issue to our environment and our economy.

I am pleased to speak today about the promising technology that could help protect our environment and safeguard our national security.

During his State of the Union Address a year ago, President Bush's spelled out his plans for efficient cars running on clean, hydrogen fuel cells. In fact, the Energy Department included $318 million for both fuel cells and hydrogen production in its 2005 budget last month. However, according to a report by the National Academy of Sciences, this plan is decades away from commercial reality. While the Bush administration anticipates mass production of hydrogen cars by 2020, the academy calls the Energy Department's goals "unrealistically aggressive."

If we don't concentrate on viable alternatives to now, the United States is expected to import 68 percent of the oil it consumes by 2025. Should hydrogen-powered fuel cells fulfill their promise, we could drastically reduce that figure and ensure our independence in a way that keeps our environment protected.

Despite the great potential of this technology, there are significant obstacles to overcome. Usable hydrogen remains expensive to produce and difficult to store effectively. At present fuel cells can cost up to ten times more than conventional engines. There is important work to do in this field, and I am proud to say that there are over a dozen organizations in my home state of Texas hard at work on solutions. Often Texas is thought of as oil country, but our state has the opportunity to play a vital role in the development of viable alternatives.

As a Ranking Member of the Research Subcommittee, I am very interested in any technology that could help keep our environment cleaner and our people more secure. I appreciate the opportunity to participate and look forward to ongoing involvement in this promising avenue of research.

[The prepared statement by Mr. Larson follows:]

PREPARED STATEMENT OF REPRESENTATIVE JOHN B. LARSON

I wanted to thank you all for testifying before the Committee today, and I just would like to take a few moments to offer this opening statement.

I've looked through the recent reports from the American Physical Society (APS) and the National Academy of Sciences (NAS), and both recommend changes to the hydrogen initiatives that argue for a greater emphasis on basic, exploratory research because of the technical barriers that must still be overcome, including cautions to DOE against premature demonstration projects.

As the Ranking Member of the Energy Subcommittee, this is an issue that I have looked closely at over the years. During debate on the Energy bill last year, I specifically worked to support a balance between the need for basic R&D with demonstration programs that would put a limited number of vehicles from different sources with different technologies in real world operating conditions.

While you are correct in identifying some of the technical hurdles that still face extensive real world deployment of fuel cell technology, especially in such areas as hydrogen storage and fuel cell freeze/cold start capability, these types of demonstrations will provide valuable benchmarking information and allow us to improve the performance of the power plants and their integration with the vehicle while longer-term efforts on hydrogen infrastructure are being pursued simultaneously.

While in general I agree that deploying large numbers of vehicles, especially using the same technological approach, is inappropriate at this time, I do support demonstration programs using limited numbers of light and heavy-duty vehicles to benchmark the actual performance of these vehicles and address system integration issues. I also believe hydrogen fuel cell buses can represent a bridging strategy that can help us explore the use of this technology while more wide spread infrastructure are explored.

For example, DOE's "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project" would do exactly that: put a limited number of light duty vehicles from different sources on the road to demonstrate their capabilities. In addition, I believe that the establishment of some form of a national fuel cell bus demonstration program would be equally important, since the hydrogen infrastructure requirements are minimal and the vehicles can perform useful work as part of the demonstration effort while providing valuable real world experience in technology development. While the National Academy suggests that DOE should give greater emphasis to fuel cell vehicle development, I would respectfully suggest that should also include the development of heavy-duty vehicles such as transit buses in cooperation with DOT and DOD.

Finally, I would like to point out that while the reports we are discussing today look at current federal hydrogen initiatives in the Department of Energy and Department of Transportation, there are additional hydrogen and fuel cell research and development initiatives being conducted within the Department of Defense that amounted to roughly $50 million in FY04 alone, and to my knowledge those research and development activities have not been directly considered in the development of this study.

I look forward to hearing your testimony, and to the opportunity for us to discuss these issues.

[The prepared statement by Mr. Honda follows:]

PREPARED STATEMENT OF REPRESENTATIVE MICHAEL M. HONDA

I thank Chairman Boehlert and Ranking Member Gordon for holding this important hearing today to consider the findings of the National Academy of Sciences and American Physical Society reports on the hydrogen initiatives and the Administration's response to the reports.

Both reports recommend that the Department of Energy shift the focus of work in the hydrogen program away from demonstration and towards more basic R&D because there are significant technical barriers to overcome. This raises several of questions that I hope this hearing will address.

Prior demonstration programs have helped to identify some of the very technical barriers this increased emphasis on research would aim to overcome. I fear that we might miss more obstacles until after we have made significant investments of time and resources if we stop working on demonstration projects.

I also wonder what role investments made in demonstration projects by other agencies can play. While not specifically directed at the light duty vehicles these reports address, I know that the Santa Clara Valley Transportation Authority's Zero Emission Bus program is funded by a transit sales tax, the Federal Transit Administration (FTA), the California Energy Commission (CEC), and the Bay Area Air Quality Management District. It will be useful to know whether DOE can work with programs like this to gain knowledge about infrastructure needs and identify potential technical obstacles that we will need to overcome.

The recommendations in these reports do not address what will happen to those demonstration programs already underway. Will a priority shift leave communities that have begun these implementation plans out in the cold? Many of these communities undertook demonstration programs to conform to environmental regulations, which seems to tie in naturally with the recommendation in the NAS report that DOE think about national policy questions that will help bring hydrogen technologies along. I worry that by giving up on early demonstration projects, we will actually stifle opportunities to develop the necessary policies and shoot ourselves in the foot.

I look forward to this hearing, and hope the witnesses can address some of these concerns.

Chairman BOEHLERT. Our panel today, our sole panel, as is tradition of this committee, is composed of three very distinguished witnesses, all of whom serve as valuable resources for this committee. We are here to learn, but we are also here to probe and question. Our panel consists of: David Garman, Assistant Secretary, Energy Efficiency and Renewable Energy at the Department of Energy; Dr. Michael Ramage, Chair, National Academy of Science Committee on Alternatives and Strategies for Future Hydrogen Production and Use; and Dr. Peter Eisenberger, Chair, American Physical Society, Panel on Public Affairs, Energy Subcommittee.

With that, I would ask all of you to try to summarize your opening statement. The Chair will not be arbitrary. And don't get nervous if you see that red light go on. That just indicates that you have exceeded five minutes, but if you want to complete a thought, or as former Secretary Richardson used to say, a paragraph, you can do so. But we are not going to be arbitrary, because what you have to say we need to hear.

Mr. Garman.

STATEMENT OF MR. DAVID GARMAN, ASSISTANT SECRETARY, ENERGY EFFICIENCY AND RENEWABLE ENERGY, DEPARTMENT OF ENERGY

Mr. GARMAN. Thank you, Mr. Chairman and Members of the Committee.

President Bush announced his Hydrogen Fuel Initiative a little more than a year ago, and the President challenged us to transform the Nation's energy future from one dependent on foreign petroleum to one that utilizes hydrogen, a fuel that can be produced from a variety of abundant domestic resources. We asked the National Academy of Sciences to evaluate our plans to transform the President's vision into reality. They did an excellent job, and we are most grateful for their work. Their report validates the President's vision with its major conclusion found on page ES–2, and I quote: "A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy sources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants," and that "there is a potential for replacing, essentially, all gasoline with hydrogen over the next half-century using only domestic resources and thus eliminating all CO_2 and criteria pollutants from vehicular emissions."

Also, I was most gratified to see the Academy's recognition of the programmatic progress that we have made. On pages ES–11 and 10–10, the report states, and I quote: "The Committee is impressed by how well the hydrogen program has progressed." In all, the study made 43 key recommendations, and if you will allow me to dispense with nuance, at least for the oral statement, we fully concur with 35 of those 43 recommendations and are carefully considering the other eight. While we may not agree with every word of every statement and finding, the Committee said absolutely nothing that we dismiss out of hand, and that is truly remarkable.

The only thing that I would quarrel with had been some of the media reports, which have portrayed the long transition time, technical obstacles, and the sheer difficulty of this effort as if they were some kind of surprise. This is, of course, something we have been saying all along. In fact, the reason this is a presidential initiative announced in the State of the Union Address is because it is a difficult undertaking requiring sustained effort, government leadership, and a bipartisan commitment to get the job done. And success is, by no means, guaranteed.

There are two other points in the report that I wish to highlight in my oral testimony. First is the issue of funding. Last year, Congress underfunded the President's request for hydrogen funding in the Energy and Water Appropriations Bill by roughly $9 million and saddled us with $39 million in earmarks. Congress also underfunded the President's request for fuel cell work in the Interior Appropriations Bill by $19 million. In the Omnibus Appropriations Bill, Congress added another $5.5 million for hydrogen, all of which was earmarked. So while the hydrogen and fuel cell programs at DOE appear well funded, we are about $67 million short of the amount of unencumbered funding we had hoped to receive in fiscal year 2004 that could be focused on our program plan. As an unfortunate consequence, we will have to delay some key work in hydrogen production, storage, and technology validation, some of the very same work the National Academy highlighted in its report. I think the Academy has recognized this problem and highlighted it on page ES–12 and elsewhere in the report.

I also want to highlight one other aspect of the report, which has been largely ignored in the media and that is well known to this committee. As you know, some of my friends in the renewable energy community have criticized our hydrogen program plans, because, in addition to advancing ways to produce hydrogen using renewable energy, we are also exploring how to make hydrogen using nuclear and fossil energy resources, including coal. The Committee noted the importance of the carbon sequestration work in this endeavor, which we think is key. And it is noteworthy that the Committee also agreed with the critical need to explore methods of producing hydrogen from coal and nuclear. And this ought to put to rest, once and for all, the notion that advancing toward the hydrogen energy economy is only environmentally advantageous if and only if all of the hydrogen is derived from renewable energy.

So with that, Mr. Chairman, I will stop. I look forward to the questions and discussions that will follow. Thank you very much.

[The prepared statement of Mr. Garman follows:]

Prepared Statement of David Garman

Mr. Chairman, Members of the Committee, I appreciate the opportunity to testify today on the President's Hydrogen Fuel Initiative and FreedomCAR Partnership. My testimony will focus on the recent National Academy of Engineering and National Research Council report: *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.* I will also comment on the recent report of the American Physical Society, *The Hydrogen Initiative.*

At the outset I want to express the Department's appreciation for the valuable work performed by the National Research Council which conducted this very comprehensive study at our request. Its carefully considered recommendations and conclusions have already helped strengthen and focus DOE's hydrogen program and increased the likelihood of its success. The report will also help DOE better focus its research, priorities and funding, given the broad slate of potential hydrogen activities and technology directions. We are especially pleased to see the Committee's conclusion that "transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy sources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants."

Hydrogen Fuel Initiative

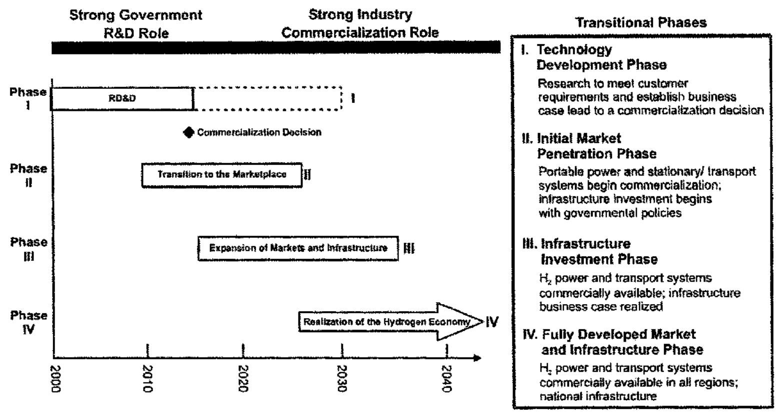
Mr. Chairman, it was a little more than one year ago that the President announced a pioneering plan to transform the Nation's energy future from one dependent on foreign petroleum to one that utilizes the most abundant element in the universe—hydrogen. This solution holds the potential to provide virtually limitless clean, safe, secure, affordable, and reliable energy from domestic resources. To achieve this vision, the President proposed that the Federal Government significantly increase its investment in hydrogen infrastructure research and development (R&D), including hydrogen production, storage, and delivery technologies, as well as fuel cells, with the goal of enabling an industry decision by 2015 to commercialize hydrogen fuel cell vehicles.

This vision is now shared around the world. Last fall, at the urging of Secretary Abraham, 15 nations, including the United States and the European Union, agreed to establish the International Partnership for the Hydrogen Economy (IPHE). The IPHE is providing a mechanism to efficiently organize and coordinate multinational research, development and deployment programs that advance the transition to a global hydrogen economy. The IPHE partners represent more than 85 percent of the world's gross domestic product and two thirds of the world's energy consumption and greenhouse gas emissions.

At a March 5, 2003 hearing before this committee, I described in detail DOE's plans to help turn the concept of a hydrogen-based economy into reality. At the time we described how we would integrate our ongoing and future hydrogen R&D activities into a focused Hydrogen Program, and how we would integrate technology for hydrogen production (from fossil, nuclear, and renewable resources), infrastructure development (including delivery and storage), fuel cells, and other technologies. We also described how we would coordinate hydrogen activities within DOE and among the federal agencies to achieve the technical milestones on the road to a hydrogen economy.

We discussed the challenges to be faced and how we believed they could be met. We said that achieving a hydrogen-based economy would require a combination of technological breakthroughs, market acceptance, and large investments in a national hydrogen energy infrastructure. We knew that success would not happen overnight, or even over years, but rather over decades. We knew it would be a long-term process that would phase hydrogen in as the technologies and their markets are ready, and that success would require that the technologies to utilize hydrogen fuel and the availability of hydrogen fuel occur simultaneously.

Also at that hearing, I presented the following timeline:



As you can see, the timeline shows that we won't realize the full potential of a hydrogen economy for several decades. Phase I technology development will lead to a commercialization decision by industry only if government-sponsored and private research is successful in meeting customer requirements and in establishing a business case that can convince industry to invest. If industry makes a positive commercialization decision, we will be ready to take the next steps toward realizing the full potential of the hydrogen economy, a process that will evolve over several decades, and may include policy options other than research to catalyze infrastructure investment. The impact of hydrogen fuel cell vehicles will depend on how quickly the market introduces the new vehicles, the availability of production and delivery infrastructure, and the time it takes for a new fleet of hydrogen vehicles to replace the existing inventory of conventional vehicles.

Our focus today is the research and development to overcome the technical barriers associated with hydrogen and fuel cell technologies—including lowering the cost of hydrogen production and fuel cell technologies, improving hydrogen storage systems, and developing codes and standards for hydrogen handling and use. The Department has requested $227 million in its FY 2005 budget request to support the Hydrogen Fuel Initiative. In addition, the Department of Transportation requested about $1.0 million.

Over the past year our progress has increased confidence that the 2015 goal is realistic and attainable. For example:

- Significant technical progress has been made in reducing the cost of hydrogen production. We have verified the ability to produce hydrogen from natural gas at $3.60 per gallon of gasoline equivalent from an integrated hydrogen refueling station that co-produces electricity from a stationary fuel cell. This meets our 2003 interim milestone.
- In the very near future, we will announce selections from two major competitive solicitations. The first is our hydrogen storage "Grand Challenge." Novel approaches, beyond pressurized tanks, are needed in the long term to provide the greater than 300 mile range that consumers expect. Our new hydrogen storage selections have established three "Centers of Excellence" where each center is composed of a national lab teamed with seven or eight universities to research novel materials for hydrogen storage.
- The second major solicitation is for our national fuel cell vehicle and hydrogen infrastructure "learning" demonstration. This "demonstration" is an extension of our research and will provide us the necessary data to focus our research on the most difficult technical barriers and safety issues, as well as help us identify vehicle-infrastructure interface issues that need to be worked out collectively by the government, automotive manufacturers and energy industry.
- In the coming months, we will also be announcing winners to our hydrogen production and delivery research solicitation.

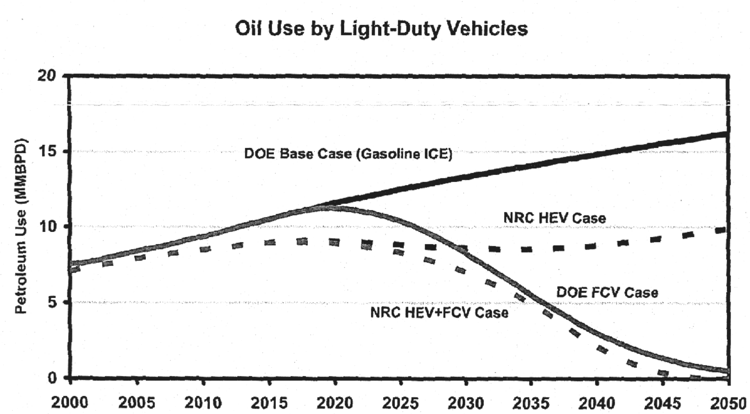
To track the progress of our research, the Department and its industry partners jointly develop performance-based technical and cost milestones that reflect customer requirements and the business case needed for industry to invest. Our newly released Hydrogen Posture Plan details the Department's overall integrated plan, identifies key technology milestones, and includes timelines that provide clear and quantifiable measures to track and demonstrate progress. We do not believe that these milestones are unrealistic. They are, however, intentionally aggressive so that we "set the bar high" to try to stimulate revolutionary ideas in research. Having said that, we plan to evaluate all of the milestones based on the National Academies' report. Indeed, the Hydrogen Posture Plan already takes into account many of the report's comments.

Our focus on hydrogen fuel cell vehicles does not come at the expense of support for conservation and gasoline hybrid vehicles as short-term strategy for reducing oil use, criteria pollutants and greenhouse gas emissions. Under the FreedomCAR Partnership, in addition to research on fuel cells, the Department requests $91 million to continue research to develop advanced, affordable hybrid component technologies. These technologies include energy storage devices, power electronics, lightweight materials, advanced combustion engines, and other technologies that have application for the gasoline hybrids of today, the fuel cell vehicles of tomorrow, or in many cases, both. The Department continues to implement robust programs in support of wind turbines, solar photovoltaic technology, Generation IV nuclear power systems, and solid state lighting, and many other energy technology program areas.

However, as the National Academies' report notes, it will take a revolutionary approach like hydrogen fuel cells to provide the fundamental change that will allow us to be completely independent of oil and free of carbon in the tailpipe. Incremental changes available in the near term will not overcome the increasing demands for a limited supply of oil.

This is demonstrated in the chart titled "Oil Use by Light Duty Vehicles." The National Academies' National Research Council report shows a case where gasoline hybrid electric vehicles (HEV), the "NRC HEV Case," penetrate the market. As you can see, under this scenario, petroleum use stays constant at best and we don't reduce our vulnerabilities associated with importing foreign oil since domestic production stays constant. When you consider the growth of petroleum use around the world, especially in developing countries, there will be an even greater demand for limited supplies.

Fuel cell vehicle (FCV) market penetration scenarios developed by DOE and the National Academies' National Research Council (NRC) are similar. As shown in the chart, the petroleum use from the "DOE FCV" case is very similar to the "NRC HEV + FCV" case. This analysis also shows that in the long-term, increased fuel economy alone will not even reduce the amount of oil use compared to today's level. Simply put, if we are going to significantly reduce our dependence on foreign oil, we need to substitute for petroleum.



Response to National Academies Report

DOE fully recognized the complexity and uncertainties involved in a transition to a hydrogen economy, and requested the National Academies to conduct an independent review of our hydrogen production and infrastructure options. We requested assistance in two major areas: (1) assessing strategies for hydrogen production from domestic resources in near-, mid-, and long-term; and (2) reviewing the Department's current research plans and making recommendations on research strategies.

Last April, the committee provided us with four interim recommendations, which we acted upon immediately. They are:

1. **The Department should establish an independent systems engineering and analysis group.** In response to this recommendation we conducted a nationwide recruiting effort and hired a lead systems integrator. The systems integrator has been tasked to develop a model to assess the impact of various technology pathways, identify key cost drivers and technological gaps, and assist in prioritization of R&D directions. A portion of the increase in the FY 2005 budget request will be used to create this capability.
2. **The Department should give exploratory and fundamental research additional budgetary emphasis.** As a result of this recommendation, the DOE Office of Science is now directly involved in supporting the President's Hydrogen Fuel Initiative. Last May, the Office of Science hosted a workshop to identify the basic research needs for a hydrogen economy. The Office of Science created and filled a position for Senior Advisor for Applied Energy Programs. This person has a broad knowledge of the Science R&D programs at the National Laboratories, and helps the applied programs in their search for technological breakthroughs. The Department's FY 2005 budget request includes $29 million for the Office of Science to conduct basic research in hydrogen production, storage and use.
3. **DOE should make a significant effort to address safety issues.** In response, we developed guidelines for safety plans to be carried out on all projects and established a safety review panel to evaluate implementation of these plans. In addition, the Department's FY 2005 budget request includes a three-fold increase in funding for safety-related research. We have also worked closely with the Department of Transportation, the National Institute of Science and Technology, and other organizations to define roles and responsibilities for the research and development of hydrogen codes and standards to enable safe use of hydrogen.
4. **DOE should integrate hydrogen R&D efforts across the applied energy programs, the Office of Science, and appropriate industry partners.** The Department's Hydrogen Posture Plan integrates the hydrogen activities supporting the President's Hydrogen Fuel Initiative across the renewable energy, fossil energy, science, and nuclear energy offices. This plan lays the foundation for a coordinated response to the President's goal for accelerated research on critical path hydrogen and fuel cell technologies. We have also expanded our existing FreedomCAR Partnership to include major energy companies (ExxonMobil, ConocoPhillips, ChevronTexaco, BP and Shell) along with all three major U.S. auto manufacturers.

The final report of the committee presented us with two main themes:

Theme 1: There should be a shift away from some development areas towards more exploratory work.

The Department has already begun shifting towards more exploratory research. A good example is in the hydrogen storage area, where we are establishing three "Centers of Excellence" led by national laboratories along with multiple university and industry partners. This could be a model for "expert" centers focusing on other priority research areas such as fuel cell costs and durability, distributed hydrogen production costs and efficiency, systems analysis for hydrogen delivery, and renewable hydrogen production methods such as photobiological, photo-electrochemical (direct solar conversion) and thermochemical (splitting water with heat processes).

The Department's mix of funding according to OMB circular A–11 for the FY 2005 budget request is as follows:

Basic Research:	12.9%
Applied Research:	42.5%
Development:	29.2%
Demonstration:	13.4%
Deployment:	2.0%

This mix reflects our shift towards more exploratory R&D in the hydrogen storage area. We are currently evaluating our fuel cell cost and durability research to see if more exploratory R&D is appropriate. I want to caution everyone that "exploratory" R&D is not synonymous with "basic" R&D. We believe the committee is recommending that we shift away from some development work that industry is capable of doing.

Theme 2: The hydrogen transition may best be accomplished through distributed production at fueling sites, from natural gas reforming or water electrolysis from wind or solar energy. The committee recommends increased R&D investments on these distributed hydrogen technologies, which will supply hydrogen for the early transitional period, and suggests allowing the long-term hydrogen economy to evolve.

Based on this recommendation, the Department will increase its focus on exploratory research to reduce costs and increase efficiency of water electrolysis and distributed natural gas reforming. In this recommendation, we believe the National Academies' committee is telling us not to over manage the long term, that the longer-term hydrogen economy should "evolve" through greater emphasis on breakthroughs in technologies with longer time horizons for commercial application, such as carbon capture and sequestration to enable coal as a long-term resource, photoelectrochemical, photobiological, and thermochemical methods.

In keeping with this recommendation, the Office of Science is now established as a direct participant in the President's initiative and we are directing our applied research into more exploratory technologies. As mentioned earlier, our hydrogen storage "Grand Challenge" will create three Centers of Excellence involving federal laboratories, universities, and private industry. We agree with the need to support exploratory research and will shift our program activities to a more basic and exploratory nature, as appropriate.

Response to American Physical Society Report

The American Physical Society report on hydrogen calls for more spending on basic research and contends that demonstrations are premature. On the second part of this recommendation, DOE along with its industry partners believe there is a clear need for such "learning" demonstrations. These demonstrations serve as extensions of our research, and are aimed at obtaining performance and durability data in real world environments. I want to stress that these are not demonstrations geared toward commercialization. There is no formula that can tell us that we have achieved a certain percentage of our target and that it is now time to conduct a demonstration to close the final gap. At this stage in the development, technology costs are reduced through research breakthroughs in materials, performance, and manufacturing technology, not "commercial" demonstrations.

Learning demonstrations, however, will provide improved understanding of the impact of various climatic conditions on fuel cell performance and durability. Such data are crucial to resolving system barriers such as water and heat management within the fuel cell. At the conclusion of the five-year demonstration program, the pre-established targets of 2,000 hours durability, 250 mile range and $3.00 per gallon gasoline equivalent are to be met by industry. This demonstration effort will give us the statistical evidence that adequate progress is being made to meet the 2015 criteria of 5,000 hours durability, 300 mile range and $1.50–$2.00 per gallon gasoline equivalent. These demonstrations will provide accelerated data that we will need to refocus our future R&D, and will provide the hard data needed to make difficult decisions should we experience a lack of research progress.

In a hydrogen economy, we will need multiple and complex interfaces among production, delivery, storage, conversion and end-use. Auto manufacturers, energy companies, and component suppliers will need to work together over the next several years to resolve such issues as the vehicle-infrastructure refueling interfaces. If we are going to make the huge transformation to a hydrogen energy system, it will be private companies, not the government, to make the investment and build the automotive manufacturing infrastructure and hydrogen production and delivery infrastructure. This learning demonstration will reveal potential solutions to overcoming technical and economic hurdles to building infrastructure.

The learning demonstration will also reveal potential safety issues and open a door to cooperation with local jurisdictions on uniform codes and standards. In summary, we believe that limited learning demonstrations, utilizing less than 15 percent of the overall hydrogen program budget and with industry cost-sharing at a 1:1 ratio, will provide us with the practical experience and critical data to ensure that our applied and exploratory research efforts are focused on the right problems.

Conclusion

Mr. Chairman, all the panelists here today will agree that achieving the vision of the hydrogen energy future is a great challenge. It will require careful planning and coordination, public education, technology development, and substantial public and private investments. It will require a broad political consensus and a bipartisan approach. Most of all, it will take leadership and resolve. By being bold and innovative, we can change the way we do business here in America; we can change our dependence upon foreign sources of energy; we can help with the quality of the air; and we can make a fundamental difference for the future of our children. This committee in particular has been instrumental in providing that kind of leadership over the years, and we look forward to continuing this dialogue in the months and years ahead.

We at the Department of Energy welcome the challenge and opportunity to play a vital role in this nation's energy future and to support our national security in such a fundamental way. This completes my prepared statement. I would be happy to answer any questions you may have.

BIOGRAPHY FOR DAVID GARMAN

David Garman was nominated by President George W. Bush to serve as Assistant Secretary on April 30, 2001 and was confirmed unanimously by the United States Senate on May 25, 2001.

Assistant Secretary Garman leads the Office of Energy Efficiency and Renewable Energy (EERE) comprised of over 500 federal employees in Washington, DC and six regional offices, supported by thousands of federal contractors both in and outside the National Laboratories. EERE's $1.2 billion technology portfolio is the largest energy research, development, demonstration and deployment portfolio at the Department of Energy.

Assistant Secretary Garman was instrumental in the development of the FreedomCAR cooperative automotive research partnership and the President's Hydrogen Fuel Initiative. In recognition of his role, he was awarded the National Hydrogen Association's 2002 Meritorious Service Award, and the Electric Drive Vehicle Association's 2003 "E–Visionary" Award. Concurrent with his duties as Assistant Secretary, Garman also serves as Chairman of the FreedomCAR Executive Steering Committee and as Chairman of the Steering Committee for the 15-nation International Partnership for a Hydrogen Economy.

During his tenure at the Department, Mr. Garman has reorganized the Office of Energy Efficiency and Renewable Energy, replacing an outdated and fragmented organization with what is arguably the most innovative business model ever employed in the Federal Government. The new EERE organization is comprised of fewer management layers, is more agile, and is focused on results rather than process. The new organization has been recognized as a success by the White House and the National Association of Public Administration. In fully implementing the new business model in accordance with the President's Management Agenda, Assistant Secretary Garman is continuing his emphasis on increasing program manager accountability, reducing administrative overhead, and getting more work performed with each taxpayer dollar.

Prior to joining the Department of Energy, Mr. Garman served in a variety of positions on the staff of two U.S. Senators and two Senate Committees during a career spanning nearly 21 years, including service on the Professional Staff of the Senate Select Committee on Intelligence and the Senate Committee on Energy and Natural Resources. Immediately prior to his current position, Mr. Garman was Chief of Staff to Frank Murkowski then Chairman of the Energy and Natural Resources Committee, now Governor of Alaska. In addition to his normal Senate duties, Mr. Garman represented the Senate leadership at virtually all of the major negotiations under the United Nations Framework Convention on Climate Change from 1995–2000.

Assistant Secretary Garman has testified before Congress as an Administration witness on more than twenty-five occasions; and been featured as a key Administration spokesman on future energy technologies in print, television and radio. He holds a Bachelor of Arts in Public Policy from Duke University, and a Master of Science in Environmental Sciences from the Johns Hopkins University.

Chairman BOEHLERT. Thank you very much.

And Dr. Ramage, you are up next. And before you start, just let me say how much we appreciate the outstanding work of the Academy. And I can't say that often enough. I do appreciate it. The floor is yours, sir.

Microphone, please.

STATEMENT OF DR. MICHAEL P. RAMAGE, CHAIR, NATIONAL ACADEMY OF SCIENCES COMMITTEE ON ALTERNATIVES AND STRATEGIES FOR FUTURE HYDROGEN PRODUCTION AND USE

Dr. RAMAGE. I am sorry.

Good afternoon, Mr. Chairman. I serve as Chairman of the National Research Council Committee on Alternatives and Strategies for Future Hydrogen Production and Use.

In the summer of 2002, the Department of Energy asked the NRC to examine the technical and policy issues, which must be addressed to attain the benefits of a hydrogen economy. Our committee reviewed the current and potential states of technologies for hydrogen production, distribution, dispensing, storage, and end use, and then we estimated cost, carbon dioxide emissions, and energy efficiencies based on that.

We also developed economic models of the technologies and developed a framework of how hydrogen could transform the U.S. energy system, and we focused on light-duty transportation. And based on the above, we reviewed the DOE program and we made recommendations on R&D strategies and priorities and directions.

The Committee reached four major conclusions in our February 2004 report. The first is that a transition to hydrogen as a major fuel could fundamentally transform the U.S. energy system, and hydrogen has the potential to replace essentially all gasoline and virtually all CO_2 from vehicular emissions.

The second, the Committee's analysis shows that there are significant hurdles on the path to a hydrogen economy. The hydrogen system must be economic. It must be safe and appealing, and it must offer energy security and environmental benefits. For the transportation sector, that means that it is essential that there is progress in fuel cell development and also in hydrogen storage, distribution, and production systems. And success is not certain, and success should not be assumed to be certain in some activity like this that has such a large benefit and also some major hurdles in front of it.

The Committee's third major conclusion addresses the transition to a hydrogen fuel system, which will probably be lengthy. Since it will be difficult to stimulate investment in large, centralized hydrogen production and distribution systems without proven demand, the Committee strongly suggests that the transition be progressed with small, on-site hydrogen production systems at the filling station. These distributed production units could be natural gas reformers. They could be water electrolyzers. And this type of transition also allows for the development of new technologies and concepts for the eventual widespread use of hydrogen.

The Committee's fourth major conclusion addresses how hydrogen could transform the energy system in the long-term, significantly reducing the energy imports and CO_2.

Switching to hydrogen will require four things. First, is that hydrogen fuel cells can penetrate the market and fully penetrate the market, that hydrogen distribution infrastructure can be developed. Hydrogen can be economically produced from coal coupled with CO_2 sequestration and the CO_2-free hydrogen production technologies can be developed from renewable sources or nuclear heat.

While the impacts will probably be small for the next 25 years, successful research and development coupled with large hydrogen and fuel cell investments will result in major impacts in the longer-term.

And based on our analysis of the hydrogen economy and a review of the DOE program, the Committee recommended that five areas of the DOE program receive increased emphasis. And the first is that breakthrough research in fuel cell vehicle development, and I emphasize breakthrough research. This is the DOE program we are talking about. The second is development of a low-cost, distributed hydrogen generation system. The third is increased effort in infrastructure analysis and research. The fourth is an early evaluation of the viability of CO_2 sequestration, particularly with its importance to coal. And the fifth is hydrogen production directly from renewables and nuclear without going through the step of electricity.

[The prepared statement of Dr. Ramage follows:]

PREPARED STATEMENT OF MICHAEL P. RAMAGE

Mr. Chairman and Members of the Committee:

My name is Michael Ramage and I served as Chairman of the National Research Council Committee on Alternatives and Strategies for Future Hydrogen Production and Use. The Research Council—known as the NRC—is the operating arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine, chartered by Congress in 1863 to advise the government on matters of science and technology. The National Research Council appointed the Committee on Alternatives and Strategies for Future Hydrogen Production and Use in the fall of 2002 to address the complex subject of the "hydrogen economy." In particular, the committee carried out these tasks:

- Assessed the current state of technology for producing hydrogen from a variety of energy sources;
- Made estimates on a consistent basis of current and future projected costs, carbon dioxide (CO_2) emissions, and energy efficiencies for hydrogen technologies;
- Considered scenarios for the potential penetration of hydrogen into the economy and associated impacts on oil imports and CO_2 gas emissions;
- Addressed the problem of how hydrogen might be distributed, stored, and dispensed to end uses-together with associated infrastructure issues—with particular emphasis on light-duty vehicles in the transportation sector;
- Reviewed the U.S. Department of Energy's (DOE's) research, development, and demonstration (RD&D) plan for hydrogen; and
- Made recommendations to the DOE on RD&D, including directions, priorities, and strategies.

The vision of the hydrogen economy is based on two expectations: (1) that hydrogen can be produced from domestic energy sources in a manner that is affordable and environmentally benign, and (2) that applications using hydrogen—fuel cell vehicles, for example—can gain market share in competition with the alternatives. To the extent that these expectations can be met, the United States, and indeed the world, would benefit from reduced vulnerability to energy disruptions and improved environmental quality, especially through lower carbon emissions. However, before this vision can become a reality, many technical, social, and policy challenges must be overcome. This report focuses on the steps that should be taken to move toward the hydrogen vision and to achieve the sought-after benefits. The report focuses exclusively on hydrogen, although it notes that alternative or complementary strategies might also serve these same goals well.

The Executive Summary presents the basic conclusions of the report[1] and the major recommendations of the committee. The report's chapters present additional findings and recommendations related to specific technologies and issues that the committee considered.

BASIC CONCLUSIONS

As described below, the committee's basic conclusions address four topics: implications for national goals, priorities for research and development (R&D), the challenge of transition, and the impacts of hydrogen-fueled light-duty vehicles on energy security and CO_2 emissions.

Implications for National Goals

A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy sources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants.[2] In his State of the Union address of January 28, 2003, President Bush moved energy, and especially hydrogen for vehicles, to the forefront of the U.S. political and technical debate. The President noted: "A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom so that the first car driven by a child born today could be powered by hydrogen, and pollution-free."[3] This committee believes that investigating and conducting RD&D activities to determine whether a hydrogen economy might be realized are important to the Nation. There is a potential for replacing essentially all gasoline with hydrogen over the next half century using only domestic resources. And there is a potential for eliminating almost all CO_2 and criteria pollutants from vehicular emissions. However, there are currently many barriers to be overcome before that potential can be realized.

Of course there are other strategies for reducing oil imports and CO_2 emissions, and thus the DOE should keep a balanced portfolio of R&D efforts and continue to explore supply-and-demand alternatives that do not depend upon hydrogen. If battery technology improved dramatically, for example, all-electric vehicles might become the preferred alternative. Furthermore, hybrid electric vehicle technology is commercially available today, and benefits from this technology can therefore be realized immediately. Fossil-fuel-based or biomass-based synthetic fuels could also be used in place of gasoline.

Research and Development Priorities

There are major hurdles on the path to achieving the vision of the hydrogen economy; the path will not be simple or straightforward. Many of the committee's observations generalize across the entire hydrogen economy: the hydrogen system must be cost-competitive, it must be safe and appealing to the consumer, and it would preferably offer advantages from the perspectives of energy security and CO_2 emissions. Specifically for the transportation sector, dramatic progress in the development of fuel cells, storage devices, and distribution systems is especially critical. Widespread success is not certain.

The committee believes that for hydrogen-fueled transportation, the four most fundamental technological and economic challenges are these:

1. *To develop and introduce cost-effective, durable, safe, and environmentally desirable fuel cell systems and hydrogen storage systems.* Current fuel cell life-

[1] The committee's final report—*The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*—was released in February, 2004 and is available at www.nap.edu.

[2] Criteria pollutants are air pollutants (e.g., lead, sulfur dioxide, and so on) emitted from numerous or diverse stationary or mobile sources for which National Ambient Air Quality Standards have been set to protect human health and public welfare.

[3] *Weekly Compilation of Presidential Documents.* Volume 39, Number 5. p. 111. Monday, February 3, 2003. Government Printing Office: Washington, D.C.

times are much too short and fuel cell costs are at least an order of magnitude too high. An on-board vehicular hydrogen storage system that has an energy density approaching that of gasoline systems has not been developed. Thus, the resulting range of vehicles with existing hydrogen storage systems is much too short.

2. *To develop the infrastructure to provide hydrogen for the light-duty vehicle user.* Hydrogen is currently produced in large quantities at reasonable costs for industrial purposes. The committee's analysis indicates that at a future, mature stage of development, hydrogen (H_2) can be produced and used in fuel cell vehicles at reasonable cost. The challenge, with today's industrial hydrogen as well as tomorrow's hydrogen is the high cost of distributing H_2 to dispersed locations. This challenge is especially severe during the early years of a transition, when demand is even more dispersed. The costs of a mature hydrogen pipeline system would be spread over many users, as the cost of the natural gas system is today. But the transition is difficult to imagine in detail. It requires many technological innovations related to the development of small-scale production units. Also nontechnical factors such as financing, siting, security, environmental impact, and the perceived safety of hydrogen pipelines and dispensing systems will play a significant role. All of these hurdles must be overcome before there can be widespread hydrogen use. An initial stage during which hydrogen is produced at small scale near the small user seems likely. In this case, production costs for small production units must be sharply reduced, which may be possible with expanded research.
3. *To reduce sharply the costs of hydrogen production from renewable energy sources, over a time frame of decades.* Tremendous progress has been made in reducing the cost of making electricity from renewable energy sources. But making hydrogen from renewable energy through the intermediate step of making electricity, a premium energy source, requires further breakthroughs in order to be competitive. Basically, these technology pathways for hydrogen production make electricity, which is converted to hydrogen, which is later converted by a fuel cell back to electricity. These steps add costs and energy losses that are particularly significant when the hydrogen competes as a commodity transportation fuel—leading the committee to believe most current approaches—except possibly that of wind energy—need to be redirected. The committee believes that the required cost reductions can be achieved only by targeted fundamental and exploratory research on hydrogen production by photobiological, photochemical, and thin-film solar processes.
4. *To capture and store ("sequester") the carbon dioxide byproduct of hydrogen production from coal.* Coal is a massive domestic U.S. energy resource that has the potential for producing cost-competitive hydrogen. However, coal processing generates large amounts of CO_2. In order to reduce CO_2 emissions from coal processing in carbon-constrained future, massive amounts of CO_2 would have to be captured and safely and reliably sequestered for hundreds of years. Key to the commercialization of a large-scale, coal-based hydrogen production option (and also for natural-gas-based options) is achieving broad public acceptance, along with additional technical development, for CO_2 sequestration.

For a viable hydrogen transportation system to emerge, all four of these challenges must be addressed.

The Challenge of Transition

There will likely be a lengthy transition period during which fuel cell vehicles and hydrogen are not competitive with internal combustion engine vehicles, including conventional gasoline and diesel fuel vehicles, and hybrid gasoline electric vehicles. The committee believes that the transition to a hydrogen fuel system will best be accomplished initially through distributed production of hydrogen, because distributed generation avoids many of the substantial infrastructure barriers faced by centralized generation. Small hydrogen-production units located at dispensing stations can produce hydrogen through natural gas reforming or electrolysis. Natural gas pipelines and electricity transmission and distribution systems already exist; for distributed generation of hydrogen, these systems would need to be expanded only moderately in the early years of the transition. During this transition period, distributed renewable energy (e.g., wind or solar energy) might provide electricity to onsite hydrogen production systems, particularly in areas of the country where electricity costs from wind or solar energy are particularly low. A transition emphasizing distributed production allows time for the development of new technologies and concepts capable of potentially overcoming the challenges facing the widespread use of hydrogen. The distributed transition approach allows time for the market to develop before too much fixed investment is set in place. While this approach allows time for the ultimate hydrogen infrastructure to emerge, the committee believes that it cannot yet be fully identified and defined.

Impacts of Hydrogen-Fueled Light-Duty Vehicles

Several findings from the committee's analysis (see Chapter 6) show the impact on the U.S. energy system if successful market penetration of hydrogen fuel cell vehicles is achieved. In order to analyze these impacts, the committee posited that fuel cell vehicle technology would be developed successfully and that hydrogen would be available to fuel light-duty vehicles (cars and light trucks). These findings are as follows:

- The committee's upper-bound market penetration case for fuel cell vehicles, premised on hybrid vehicle experience, assumes that fuel cell vehicles enter the U.S. light-duty vehicle market in 2015 in competition with conventional and hybrid electric vehicles, reaching 25 percent of light-duty vehicle sales around 2027. The demand for hydrogen in about 2027 would be about equal to the current production of nine million short tons (tons) per year, which would be only a small fraction of the 110 million tons required for full replacement of gasoline light-duty vehicles with hydrogen vehicles, posited to take place in 2050.
- If coal, renewable energy, or nuclear energy is used to produce hydrogen, a transition to a light-duty fleet of vehicles fueled entirely by hydrogen would reduce total energy imports by the amount of oil consumption displaced. However, if natural gas is used to produce hydrogen, and if, on the margin, natural gas is imported, there would be little if any reduction in total energy imports, because natural gas for hydrogen would displace petroleum for gasoline.
- CO_2 emissions from vehicles can be cut significantly if the hydrogen is produced entirely from renewables or nuclear energy, or from fossil fuels with sequestration of CO_2. The use of a combination of natural gas without sequestration and renewable energy can also significantly reduce CO_2 emissions. However, emissions of CO_2 associated with light-duty vehicles contribute only a portion of projected CO_2 emissions; thus, sharply reducing overall CO_2 releases will require carbon reductions in other parts of the economy, particularly in electricity production.
- Overall, although a transition to hydrogen could greatly transform the U.S. energy system in the long run, the impacts on oil imports and CO_2 emissions are likely to be minor during the next 25 years. However, thereafter, if R&D is successful and large investments are made in hydrogen and fuel cells, the impact on the U.S. energy system could be great.

MAJOR RECOMMENDATIONS

Systems Analysis of U.S. Energy Options

The U.S. energy system will change in many ways over the next 50 years. Some of the drivers for such change are already recognized, including at present the geology and geopolitics of fossil fuels and, perhaps eventually, the rising CO_2 concentration in the atmosphere. Other drivers will emerge from options made available by new technologies. The U.S. energy system can be expected to continue to have substantial diversity; one should expect the emergence of neither a single primary energy source nor a single energy carrier. Moreover, more-energy-efficient technologies for the household, office, factory, and vehicle will continue to be developed and introduced into the energy system. The role of the DOE hydrogen program[4] in the restructuring of the overall national energy system will evolve with time.

To help shape the DOE hydrogen program, the committee sees a critical role for systems analysis. Systems analysis will be needed both to coordinate the multiple parallel efforts within the hydrogen program and to integrate the program within a balanced, overall DOE national energy R&D effort. Internal coordination must address the many primary sources from which hydrogen can be produced, the various scales of production, the options for hydrogen distribution, the crosscutting challenges of storage and safety, and the hydrogen-using devices. Integration within the

[4] The words "hydrogen program" refer collectively to the programs concerned with hydrogen production, distribution, and use within DOE's Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy, Office of Science, and Office of Nuclear Energy, Science and Technology. There is no single program with this title.

overall DOE effort must address the place of hydrogen relative to other secondary energy sources—helping, in particular, to clarify the competition between electricity, liquid-fuel-based (e.g., cellulosic ethanol), and hydrogen-based transportation. This is particularly important as clean alternative fuel internal combustion engines, fuel cells and batteries evolve. Integration within the overall DOE effort must also address interactions with end-use energy efficiency, as represented, for example, by high-fuel-economy options such as hybrid vehicles. Implications of safety, security, and environmental concerns will need to be better understood. So will issues of timing and sequencing: depending on the details of system design, a hydrogen transportation system initially based on distributed hydrogen production, for example, might or might not easily evolve into a centralized system as density of use increases.

Recommendation ES–1. The Department of Energy should continue to develop its hydrogen initiative as a potential long-term contributor to improving U.S. energy security and environmental protection. The program plan should be reviewed and updated regularly to reflect progress, potential synergisms within the program, and interactions with other energy programs and partnerships (e.g., the California Fuel Cell Partnership). In order to achieve this objective, the committee recommends that the DOE develop and employ a systems analysis approach to understanding full costs, defining options, evaluating research results, and helping balance its hydrogen program for the short, medium, and long term. Such an approach should be implemented for all U.S. energy options, not only for hydrogen.

As part of its systems analysis, the DOE should map out and evaluate a transition plan consistent with developing the infrastructure and hydrogen resources necessary to support the committee's hydrogen vehicle penetration scenario or another similar demand scenario. The DOE should estimate what levels of investment over time are required—and in which program and project areas—in order to achieve a significant reduction in carbon dioxide emissions from passenger vehicles by mid-century.

Fuel Cell Vehicle Technology

The committee observes that the Federal Government has been active in fuel cell research for roughly 40 years, while proton exchange membrane (PEM) fuel cells applied to hydrogen vehicle systems are a relatively recent development (as of the late 1980s). In spite of substantial R&D spending by the DOE and industry, costs are still a factor of 10 to 20 times too expensive, are short of required durability, and energy efficiency is still too low for light-duty-vehicle applications. Accordingly, the challenges of developing PEM fuel cells for automotive applications are large, and the solutions to overcoming these challenges are uncertain.

The committee estimates that the fuel cell system, including on-board storage of hydrogen, will have to decrease in cost to less than $100 per kilowatt (kW)[5] before fuel cell vehicles (FCVs) become a plausible commercial option, and it will take at least a decade for this to happen. In particular, if the cost of the fuel cell system for light-duty vehicles does not eventually decrease to the $50/kW range, fuel cells will not propel the hydrogen economy without some regulatory mandate or incentive.

Automakers have demonstrated FCVs in which hydrogen is stored on board in different ways, primarily as high-pressure compressed gas or as a cryogenic liquid. At the current state of development, both of these options have serious shortcomings that are likely to preclude their long-term commercial viability. New solutions are needed in order to lead to vehicles that have at least a 300 mile driving range; are compact, lightweight, and inexpensive; and that meet future safety standards.

Given the current state of knowledge with respect to fuel cell durability, on-board storage systems, and existing component costs, the committee believes that the near-term DOE milestones for FCVs are unrealistically aggressive.

Recommendation ES–2. Given that large improvements are still needed in fuel cell technology and given that industry is investing considerable funding in technology development, increased government funding on research and development should be dedicated to the research on breakthroughs in on-board storage systems, in fuel cell costs, and in materials for durability in order to attack known inhibitors to the high volume production of fuel cell vehicles.

Infrastructure

A nationwide, high-quality, safe, and efficient hydrogen infrastructure will be required in order for hydrogen to be used widely in the consumer sector. While it will

[5] Cost includes fuel cell module, precious metals, fuel processor, compressed hydrogen storage, balance of plant, and assembly, labor and depreciation.

be many years before hydrogen use is significant enough to justify an integrated national infrastructure—as much as two decades in the scenario posited by the committee—regional infrastructures could evolve sooner. The relationship between hydrogen production, delivery, and dispensing is very complex, even for regional infrastructures, as it depends on many variables associated with logistics systems and on many public and private entities. Codes and standards for infrastructure development could be a significant deterrent to hydrogen advancement if not established well ahead of the hydrogen market. Similarly, since resilience to terrorist attack has become a major performance criterion for any infrastructure system, the design of future hydrogen infrastructure systems may need to consider protection against such risks.

In the area of infrastructure and delivery there seem to be significant opportunities for making major improvements. The DOE does not yet have a strong program on hydrogen infrastructures. DOE leadership is critical, because the current incentives for companies to make early investments in hydrogen infrastructure are relatively weak.

Recommendation ES–3a. The Department of Energy program in infrastructure requires greater emphasis and support. The Department of Energy should strive to create better linkages between its seemingly disconnected programs in large-scale and small-scale hydrogen production. The hydrogen infrastructure program should address issues such as storage requirements, hydrogen purity, pipeline materials, compressors, leak detection, and permitting, with the objective of clarifying the conditions under which large-scale and small-scale hydrogen production will become competitive, complementary, or independent. The logistics of interconnecting hydrogen production and end use are daunting, and all current methods of hydrogen delivery have poor energy-efficiency characteristics and difficult logistics. Accordingly, the committee believes exploratory research focused on new concepts for hydrogen delivery requires additional funding. The committee recognizes that there is little understanding of future logistics systems and new concepts for hydrogen delivery—thus making a systems approach very important.

Recommendation ES–3b. The DOE should accelerate work on codes and standards and on permitting, addressing head-on the difficulties of working across existing and emerging hydrogen standards in cities, counties, states, and the Nation.

Transition

The transition to a hydrogen economy involves challenges that cannot be overcome by research and development and demonstrations alone. Unresolved issues of policy development, infrastructure development, and safety will slow the penetration of hydrogen into the market even if the technical hurdles of production cost and energy efficiency are overcome. Significant industry investments in advance of market forces will not be made unless government creates a business environment that reflects societal priorities with respect to greenhouse gas emissions and oil imports.

Recommendation ES–4. The policy analysis capability of the Department of Energy with respect to the hydrogen economy should be strengthened, and the role of government in supporting and facilitating industry investments to help bring about a transition to a hydrogen economy needs to be better understood.

The committee believes that a hydrogen economy will not result from a straightforward replacement of the present fossil-fuel-based economy. There are great uncertainties surrounding a transition period, because many innovations and technological breakthroughs will be required to address the costs, and energy-efficiency, distribution and nontechnical issues. The hydrogen fuel for the very early transitional period, before distributed generation takes hold, would probably be supplied in the form of pressurized or liquefied molecular hydrogen, trucked from existing, centralized production facilities. But, as volume grows, such an approach may be judged too expensive and/or too hazardous. It seems likely that, in the next 10 to 30 years, hydrogen produced in distributed rather than centralized facilities will dominate. Distributed production of hydrogen seems most likely to be done with small-scale natural gas reformers or by electrolysis of water; however, new concepts in distributed production could be developed over this time period.

Recommendation ES–5. Distributed hydrogen production systems deserve increased research and development (R&D) investments by the Department of Energy. Increased R&D efforts and accelerated program timing could decrease the cost and increase the energy efficiency of small-scale natural gas reformers and water electrolysis systems. In addition, a program should be initiated to develop new concepts in distributed hydrogen production systems that have the potential to compete—in cost, energy efficiency, and safety—with centralized systems. As this program develops new concepts bearing on the safety of local hydrogen storage and delivery systems, it may be possible to apply these concepts in large-scale hydrogen generation systems as well.

Safety

Safety will be a major issue from the standpoint of commercialization of hydrogen-powered vehicles. Much evidence suggests that hydrogen can be manufactured and used in professionally managed systems with acceptable safety, but experts differ markedly in their views of the safety of hydrogen in a consumer-centered transportation system. A particularly salient and under-explored issue is that of leakage in enclosed structures, such as garages in homes and commercial establishments. Hydrogen safety, from both a technological and a societal perspective, will be one of the major hurdles that must be overcome in order to achieve the hydrogen economy.

Recommendation ES–6. The committee believes that the Department of Energy program in safety is well planned and should be a priority. However, the committee emphasizes the following:

- Safety policy goals should be proposed and discussed by Department of Energy with stakeholder groups early in the hydrogen technology development process.
- The Department of Energy should continue its work with standards development organizations and ensure increased emphasis on distributed production of hydrogen.
- The Department of Energy systems analysis should specifically include safety, and it should be understood to be an overriding criterion.
- The goal of the physical testing program should be to resolve safety issues in advance of commercial use.
- The Department of Energy's public education program should continue to focus on hydrogen safety, particularly the safe use of hydrogen in distributed production and in consumer environments.

Carbon Dioxide-Free Hydrogen

The long timescale associated with the development of viable hydrogen fuel cells and hydrogen storage provides a time window for a more intensive DOE program to develop hydrogen from electrolysis, which, if economic, has the potential to lead to major reductions in CO_2 emissions and enhanced energy security. The committee believes that if the cost of fuel cells can be reduced to $50 per kilowatt (kW), with focused research a corresponding dramatic drop in the cost of electrolytic cells to electrolyze water can be expected (to ~$125/kW). If such a low electrolyzer cost is achieved, the cost of hydrogen produced by electrolysis will be dominated by the cost of the electricity, not by the cost of the electrolyzer. Thus, in conjunction with research to lower the cost of electrolyzers, research focused on reducing electricity costs from renewable energy and nuclear energy has the potential to reduce overall hydrogen production costs substantially.

Recommendation ES–7. The Department of Energy should increase emphasis on electrolyzer development, with a target of $125 per kilowatt and a significant increase in efficiency toward a goal of over 70 percent (lower heating value basis). In such a program, care must be taken to properly account for the inherent intermittency of wind and solar energy, which can be a major limitation to their wide-scale use. In parallel, more aggressive electricity cost targets should be set for unsubsidized nuclear and renewable energy that might be used directly to generate electricity. Success in these areas would greatly increase the potential for carbon dioxide-free hydrogen production.

Carbon Capture and Storage

The DOE's various efforts with respect to hydrogen and fuel cell technology will benefit from close integration with carbon capture and storage (sequestration) activities and programs in the Office of Fossil Energy. If there is an expanded role for hydrogen produced from fossil fuels in providing energy services, the probability of achieving substantial reductions in net CO_2 emissions through sequestration will be greatly enhanced through close program integration. Integration will enable the DOE to identify critical technologies and research areas that can enable hydrogen production from fossil fuels with CO_2 capture and storage. Close integration will promote the analysis of overlapping issues such as the co-capture and co-storage with CO_2 of pollutants such as sulfur produced during hydrogen production.

Many early carbon capture and storage projects will not involve hydrogen, but rather will involve the capture of the CO_2 impurity in natural gas, the capture of

CO_2 produced at electric plants, or the capture of CO_2 at ammonia and synfuels plants. All of these routes to capture, however, share carbon storage as a common component, and carbon storage is the area in which the most difficult institutional issues and the challenges related to public acceptance arise.

Recommendation ES–8. The Department of Energy should tighten the coupling of its efforts on hydrogen and fuel cell technology with the DOE Office of Fossil Energy's programs on carbon capture and storage (sequestration). Because of the hydrogen program's large stake in the successful launching of carbon capture and storage activity, the hydrogen program should participate in all of the early carbon capture and storage projects, even those that do not directly involve carbon capture during hydrogen production. These projects will address the most difficult institutional issues and the challenges related to issues of public acceptance, which have the potential of delaying the introduction of hydrogen in the marketplace.

The Department of Energy's Hydrogen Research, Development and Demonstration Plan

As part of its effort, the committee reviewed the DOE's draft "Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan," (DOE, 2003b) dated June 3, 2003. The committee's deliberations focused only on the hydrogen production and demand portion of the overall DOE plan. For example, while the committee makes recommendations on the use of renewable energy for hydrogen production, it did not review the entire DOE renewables program in depth. The committee is impressed by how well the hydrogen program has progressed. From its analysis, the committee makes two overall observations about the program:

- First, the plan is focused primarily on the activities in the Office of Hydrogen, Fuel Cells and Infrastructure Technologies Program within the Office of Energy Efficiency & Renewable Energy, and on some activities in the Office of Fossil Energy. The activities related to hydrogen in the Office of Nuclear Energy, Science and Technology, and in the Office of Science, as well as activities related to carbon capture and storage in the Office of Fossil Energy, are important, but they are mentioned only casually in the plan. The development of an overall DOE program will require better integration across all DOE programs.
- Second, the plan's priorities are unclear, as they are lost within the myriad of activities that are proposed. A general budget is contained in the Appendix for the plan, but the plan provides no dollar numbers at the project level, even for existing projects/programs. The committee found it difficult to judge the priorities and the go/no-go decision points for each of the R&D areas.

Recommendation ES–9. The Department of Energy should continue to develop its hydrogen Research, Development, and Demonstration (RD&D) Plan to improve the integration and balance of activities within the Office of Energy Efficiency and Renewable Energy; the Office of Fossil Energy (including programs related to carbon sequestration); the Office of Nuclear Energy, Science, and Technology; and the Office of Science. The committee believes that, overall, the production, distribution, and dispensing portion of the program is probably underfunded, particularly because a significant fraction of appropriated funds is already earmarked. The committee understands that of the $78 million appropriated for hydrogen technology for FY 2004 in the Energy and Water appropriations bill (Pub. Law 108–137), $37 million is earmarked for activities that will not particularly advance the hydrogen initiative. The committee also believes that the hydrogen program, in an attempt to meet the extreme challenges set by senior government and DOE leaders, has tried to establish RD&D activities in too many areas, creating a very diverse, somewhat unfocused program. Thus, prioritizing the efforts both within and across program areas, establishing milestones and go/no-go decisions, and adjusting the program on the basis of results are all extremely important in a program with so many challenges. This approach will also help determine when it is appropriate to take a program to the demonstration stage. And finally, the committee believes that the probability of success in bringing the United States to a hydrogen economy will be greatly increased by partnering with a broader range of academic and industrial organizations—possibly including an international focus[6]—and by establishing an independent program review process and board.

Recommendation ES–10. There should be a shift in the hydrogen program away from some development areas and toward exploratory work—as has been done in the area of hydrogen storage. A hydrogen economy will require a number of technological and conceptual breakthroughs. The Department of Energy program calls for increased funding in some important exploratory research areas such as hydrogen storage and photoelectrochemical hydrogen production. However, the committee believes that much more exploratory research is needed. Other areas likely to benefit from an increased emphasis on exploratory research include delivery systems, pipeline materials, electrolysis, and materials science for many applications. The execution of such changes in emphasis would be facilitated by the establishment of DOE-sponsored academic energy research centers. These centers should focus on interdisciplinary areas of new science and engineering—such as materials research into nanostructures, and modeling for materials design—in which there are opportunities for breakthrough solutions to energy issues.

Recommendation ES–11. As a framework for recommending and prioritizing the Department of Energy program, the committee considered the following:

- Technologies that could significantly impact U.S. energy security and carbon dioxide emissions,
- The timescale for the evolution of the hydrogen economy,
- Technology developments needed for both the transition period and steady state,
- Externalities that would decelerate technology implementation, and
- The comparative advantage of the DOE in research and development of technologies at the pre-competitive stage.

The committee recommends that the following areas receive increased emphasis:

- *Fuel cell vehicle development.* Increase research and development (R&D) to facilitate breakthroughs in fuel cell costs and in durability of fuel cell materials, as well as breakthroughs in on-board hydrogen storage systems;
- *Distributed hydrogen generation.* Increase R&D in small-scale natural gas reforming, electrolysis, and new concepts for distributed hydrogen production systems;
- *Infrastructure analysis.* Accelerate and increase efforts in systems modeling and analysis for hydrogen delivery, with the objective of developing options and helping guide R&D in large-scale infrastructure development;
- *Carbon sequestration and FutureGen.* Accelerate development and early evaluation of the viability of carbon capture and storage (sequestration) on a large scale because of its implications for the long-term use of coal for hydrogen production. Continue the FutureGen Project as a high-priority task;
- *Carbon dioxide free-energy technologies.* Increase emphasis on the development of wind-energy-to-hydrogen as an important technology for the hydrogen transition period and potentially for the longer-term. Increase exploratory and fundamental research on hydrogen production by photobiological, photoelectrochemical, thin-film solar, and nuclear heat processes.

COMMITTEE ON ALTERNATIVES AND STRATEGIES FOR FUTURE HYDROGEN PRODUCTION AND USE

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[6] Secretary Abraham, joined by Ministers representing 14 nations and the European Commission, signed an agreement on November 20, 2003 to formally establish the International Partnership for the Hydrogen Economy.

[7] NAE = member, National Academy of Engineering.

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BIOGRAPHY FOR MICHAEL P. RAMAGE

Michael Ramage was born on July 29, 1943, in Washington, Indiana. He received a B.S. degree in 1966, a M.S. degree in 1969, and a Ph.D. in 1971, all in Chemical Engineering from Purdue University. He retired as Executive Vice President of ExxonMobil Research and Engineering Company in 2001. Mr. Ramage was formerly Chief Technology Officer of Mobil Oil Corporation and President, Mobil Technology Company. He was also member of the Board of Directors and Executive Committee of Mobil Oil Corporation.

Ramage joined the Mobil Research and Development Corporation in 1971, working at the Paulsboro Research Laboratory, where he held various technical and managerial positions until becoming Manager of Process Development for Mobil Chemical Company in 1980. He was named Manager of Planning Coordination for Mobil Chemical Company's domestic and international operations in 1981. He returned to the Paulsboro Research Laboratory in 1982 as Manager of the Process Research, Development, and Technical Service Division. He was named Vice President of Planning for Mobil Research and Development Corporation in 1987. From 1989–1992 he managed Mobil's Dallas Research Laboratory, which was responsible for Mobil's geoscience and petroleum engineering research efforts. In 1992, he led a team that created Mobil Exploration and Producing Technical Center, and was appointed General Manager. In this capacity, he was responsible for research, development, and technical support for Mobil's worldwide exploration and producing activities. In 1994, he was appointed Vice President of Engineering for Mobil and was responsible for leading the Corporation's worldwide Engineering Organization. In 1995, Mr. Ramage again led a major corporate reorganization effort. The result was the creation of Mobil Technology Company, a worldwide organization of over 2000 people responsible for research, engineering, technical service, and capital project management for all Mobil business units. In September 1995, he was appointed Chief Technology Office and President, Mobil Technology Company. In 1998, he was appointed to the Board of Directors and Executive Committee of Mobil Oil Corporation. In 1999, he was a member of the Exxon Mobil merger transition team and was later appointed Executive Vice President, ExxonMobil Research and Engineering Company. Mr. Ramage retired from ExxonMobil in 2002 and continues to serve as a liaison between the company and outside research, academic, and professional organizations.

Ramage did extensive research in reaction engineering and catalysis in his early career at Mobil and was awarded six U.S. patents, one New Zealand patent, and has thirteen publications for work related to those areas.

Mr. Ramage is a member of the Board of Directors for the American Institute of Chemical Engineers, the International Symposium on Chemical Reaction Engineering, and Junior Achievement of Philadelphia. He serves on the Chemical Engineering Visiting Committee at Purdue University. In the past, he served on Advisory Boards at Stanford, University of California, Berkeley, University of Texas at Austin, and The Construction Industry Institute. Mr. Ramage is also a member of the National Academy of Engineering, the NAE Council, and The Government University Industry Research Roundtable. He received an Honorary Doctor of Engineering degree from Purdue in 1996.

Dr. RAMAGE. Mr. Chairman, would you like me to answer the questions now?

Chairman BOEHLERT. Yes.

Dr. RAMAGE. Okay. With regard to the five questions, the first question regarded the appropriate balance of federal funds between demonstration and research. This issue was not directly addressed in our study, but our report does recommend a shift away from development in some areas, such as biomass gasification, or more exploratory research in areas such as direct hydrogen production using photo, biological, and solar methods.

With regards to your second question on policy analysis, the DOE must have the capability not only to manage the technical programs, but also engage in policy discussions required to move the technology into the market. Policies such as incentives and government industry actions can impact the goals and directions of the technical program.

With regard to your third question on market penetration and our model, the Committee's vision for how light-duty fuel cell vehicles will enter the U.S. market is plausible, but it is optimistic. And it is optimistic because it assumes two things. It assumes first that if—the technical barriers are overcome and second that the infrastructure barriers are overcome. If those two things happen, then it becomes plausible in our mind. Those are the two big areas. And this is the reason why. One of the major—our report was on the transition period and the transition period using small scale, at-site production systems so we can take the infrastructure issue out of the equation and let that develop over time.

With regard to your fourth question regarding demonstration programs, this issue also was not addressed in our Committee, but let me give you some personal perspective. I believe that the need and timing for demonstrations varies with the type of technology. And I believe that there are three important criteria that must be met before technology is ready for demonstration. And here, I am really talking about large-scale demonstrations like building coal plants or natural gas plants to produce hydrogen. There are three areas. The first is the individual system components of the technology needs to meet commercial performance, not necessarily cost, but commercial performance. The second is that the scale of the components, to a large scale, should be performed one at a time in existing production facilities, if possible. And I would call these learning demonstrations. And the third is that a systems modeling approach must be used to be able, with a mathematical process, which must be completed, which you can predict commercial performance, risk, and synergies, those three areas.

With respect to your fifth question, the non-hydrogen bridge technologies to a hydrogen economy, there are a number of strategies for reducing oil imports and carbon dioxide emissions in the short-, medium-, and long-term. The Committee recommends that the DOE keep a balanced program and that the systems approach be developed and employed to understand the trade-offs of all U.S. energy, including hydrogen. And this also could include, and should include, the analysis of bridge technologies to get us from one point to the next point.

Mr. Chairman, this concludes my testimony, and I will be glad to answer any questions that you may have.

Chairman BOEHLERT. Thank you very much, Dr. Ramage.

Dr. Eisenberger.

STATEMENT OF DR. PETER EISENBERGER, CHAIR, AMERICAN PHYSICAL SOCIETY, PANEL ON PUBLIC AFFAIRS, ENERGY SUBCOMMITTEE

Dr. EISENBERGER. Mr. Chairman, Mr. Gordon, Members of the Committee, thank you for the invitation to testify today.

I chair the Committee of the American Physical Society composed of scientists, industrial R&D managers, and energy economists. We analyzed the Hydrogen Initiative and released our report on Monday. I request that our report be entered into the record. *[The information referred to appears in Appendix 2: Additional Material for the Record.]*

The bottom line is that major scientific breakthroughs are required for the Hydrogen Initiative to succeed. We made several management and funding recommendations that, in our opinion, will increase the chances for long-term success.

As a starting point, let me say that currently there is only a very nascent technology base upon which to build a hydrogen economy. Currently, the U.S. industry provides hydrogen to meet the needs of a non-transportation sector that is only about three percent of what is needed for that transportation sector. Several hydrogen fueling stations are scheduled to open this year, and several models of hydrogen-fueled cars have been demonstrated, but none of the current technologies are competitive options for the consumer.

The most promising hydrogen engine technologies require 10 to 100 times improvements in cost or performance in order to be competitive. As the Secretary of Energy has stated, current hydrogen production methods are four times more expensive than gasoline and significant challenges remain to satisfy both energy security and environmental objectives of converting to a hydrogen-based transportation sector. Finally, no material exists to construct a hydrogen fuel tank that meets the consumer benchmarks. A new material must be developed.

These are very large performance gaps, and our committee concluded that incremental improvements to existing technologies are not sufficient to close all of the gaps. In particular, hydrogen storage is a potential showstopper.

Simply put, for the Hydrogen Initiative to succeed, major scientific breakthroughs are needed. This will not be easy. We can not simply engineer our way to a hydrogen economy, but we can take several steps now to make success more likely.

Without question, relevant basic science must have greater emphasis in both the planning and research program of the Hydrogen

Initiative. This is not a controversial conclusion. The Bush Administration has already taken steps in this direction, but more must be done. We recommend that: one, the Hydrogen Technical Advisory Committee include members with strong research backgrounds who are familiar with key basic science problems; two, Principal-Investigator basic research should be increased, and this PI research should be complemented with competitively-bid, peer-reviewed multidisciplinary research centers that carry out basic research in key research areas of production, storage, and use. These university-based centers should have active industry and national laboratory participation.

The issue of funding is, of course, a delicate one. Resources are not unlimited, and members of our Committee face—members of your committee face difficult decisions. Several members of our APS Committee have managed large-scale industrial technology programs. For what it is worth, I and the members of my committee feel your pain. We have faced difficult funding decisions in our own careers.

Perhaps the most useful thing I can share with you is the manner in which industry approaches the difficult funding decisions you face. The main factors involve technological competitiveness and readiness, market acceptance, and rate of penetration. In the case of Congress, one needs to add the criteria of meeting national security objectives. Our evaluation is that for hydrogen there are very significant technology gaps, a lack of an existing infrastructure, and the inevitable slow rate of penetration for a new energy technology. This means that one would invest more resources in research and less, if at all, in development projects. Pilot projects to demonstrate specific components, like sequestrations, are more appropriate at this state of the Hydrogen Initiative. And a very important point is that premature investments in large demonstration projects have a history of not only failing but also damaging the overall objectives.

However, national security objectives may argue for a more aggressive development plan than industry would follow, though still premature large-scale demonstration projects are unlikely to be helpful. In this regard, I will mention one additional point of view that the industrial managers on our APS Committee all shared: the need to hedge.

In the event that the timeline for significant hydrogen vehicle market penetration slips beyond 2020, there could be, for energy security reasons, a greater need for technologies that serve as a bridge between the current fossil fuel economy and any future hydrogen economy. Also the likelihood is increased that continued investment in research will produce new discoveries that will identify a far superior way to meet our needs in the long-term. Increasing the focus on basic science and engineering that advances such technologies would serve as a sensible hedge and, at the same time, maintain the development of technologies that show clear, short-term promise.

Similarly, the Hydrogen Initiative must not displace research into promising energy efficiency, renewable energy areas, and carbon sequestrations. These investments both complement and contribute to the goals of a hydrogen economy. And they become an increasingly important means for reducing CO_2 and enhancing our energy security in the event that the significant technology hurdles for the Initiative are not met within the proposed timeline.

I hope that our perspective has—our perspective and our recommendations help you in your oversight, and I am prepared to answer any questions you might have.

Thank you very much.

[The prepared statement of Dr. Eisenberger follows:]

PREPARED STATEMENT OF PETER EISENBERGER

Mr. Chairman, Mr. Gordon, Members of the Committee, thank you for the invitation to testify today.

In January 2003, President Bush announced an Initiative to reduce the Nation's dependence on foreign oil through the production of hydrogen fuel and a hydrogen-fueled car. The Initiative envisions the competitive use of hydrogen in commercial transportation by the year 2020.

I chaired a committee of the American Physical Society that analyzed this Initiative—we released our report on Monday. The bottom line is that major scientific breakthroughs are required for the Hydrogen Initiative to succeed. We made several management and funding recommendations that, in our opinion, will increase the chances for long-term success.

Before I get into the specifics, let me say a very brief word about our authors and methodology. Together, the authors and reviewers have considerable experience in bench science, the management of industrial technology programs from the laboratory to systems level, management of government R&D programs, and the economics of energy-commercialization programs. We did not carry out a new analysis of the scientific elements of the Hydrogen Initiative. Instead, we distilled the considerable work that is already available. Our sources included the DOE "Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use", the Hydrogen Energy Roadmap, and numerous presentations by government officials managing the Hydrogen Initiative, including those for the just released NRC report.

As a starting point, let me say that currently there is only a very nascent technology base upon which to build a hydrogen economy. Currently, the U.S. industry provides hydrogen to meet the needs of the non-transportation sector that is only about three percent of what is needed for the transportation sector. Several hydrogen-fueling stations are scheduled to open this year. And several models of hydrogen-fueled cars have been demonstrated. But, none of the current technologies are competitive options for the consumer.

The most promising hydrogen-engine technologies require 10 to 100 times improvements in cost or performance in order to be competitive. As the Secretary of Energy has stated, current hydrogen production methods are four times more expensive than gasoline, and significant challenges remain to satisfy both energy security and environmental objectives of converting to a hydrogen-based transportation sector. Finally, no material exists to construct a hydrogen fuel tank that meets the consumer benchmarks. A new material must be developed.

These are very large performance gaps. And our committee concluded that incremental improvements to existing technologies are not sufficient to close all the gaps. In particular, hydrogen storage is the potential show-stopper.

Simply put, for the Hydrogen Initiative to succeed, major scientific breakthroughs are needed. This will not be easy. We cannot simply engineer our way to a hydrogen economy. But, we can take several steps now to make success more likely.

Without question, relevant basic science must have greater emphasis in both the planning and the research program of the Hydrogen Initiative. This is not a controversial conclusion. The Bush Administration has already taken steps in this direction, but, more must be done. We recommend that:

1. The Hydrogen Technical Advisory Committee include members with strong research backgrounds who are familiar with the key basic science problems.
2. Principal-Investigator basic research should be increased. And this PI research should be complemented with competitively-bid, peer-reviewed multidisciplinary research centers that carry out basic research in the key research areas of production, storage and use. These university-based centers should have active industry and national laboratory participation.

The issue of funding is, of course, a delicate one. Resources are not unlimited and Members of your committee face difficult decisions. Several members of our APS committee have managed large-scale industrial technology programs. As for myself, in an earlier life, I was Senior Director of the Corporate Research Laboratory for Exxon. For what it's worth, I and the members of my committee, feel your pain. We have faced difficult funding decisions in our careers.

Perhaps the most useful thing I can share with you is the manner in which industries approaches these difficult funding decisions. The main factors involve technological competitiveness and readiness, market acceptance, and rate of penetration. In the case of Congress, one needs to add the criteria of meeting national security objectives. Our evaluation is that for hydrogen there are very significant technology gaps, a lack of an existing infrastructure and the inevitable slow rate of penetration for a new energy technology. This means that one would invest more resources in research and less, if at all, in development projects. Pilot projects to demonstrate specific components like sequestration are more appropriate at this stage of the Hydrogen Initiative. Premature investments in a large demonstration projects have a history of not only failing but also damaging the overall objectives.

However, national security objectives may argue for a more aggressive development plan than industry would follow, though premature large-scale demonstration projects are unlikely to be helpful. In this regard, I will mention one additional point of view that the industrial managers on our APS committee all shared—hedging.

In the event that the timeline for significant hydrogen vehicles market penetration slips beyond 2020, there could be, for energy security reasons, a greater need for technologies that serve as a "bridge" between the current fossil-fuel economy and any future hydrogen economy. Also the likelihood is increased that continued investment in research will produce new discoveries that will identify a far superior way to meet our needs in the long term. Increasing the focus on basic science and engineering that advances such technologies would serve as a sensible hedge and at the same time maintain the development of technologies that show clear short-term promise.

Similarly, the Hydrogen Initiative must not displace research into promising energy efficiency and renewable energy areas, and carbon sequestration. These investments both complement and contribute to the goals of a hydrogen economy. And, they become increasingly important means for reducing CO_2 and enhancing our energy security in the event that the significant technology hurdles for the Initiative are not met within the proposed timeline.

I hope that our perspective and our recommendations help in your oversight of the Hydrogen Initiative.

Biography for Peter Eisenberger

Peter Eisenberger attended Princeton University from 1959 until 1963 where he received a B.A. in Physics. He graduated in 1967 from Harvard with a Ph.D. in Applied Physics and remained at Harvard for one year as a Post-Doctoral Fellow. In 1968, Dr. Eisenberger joined the staff at Bell Laboratories. From 1974 to 1981, he was a department head at Bell Laboratories. He was a consulting professor at Stanford University's Applied Physics Department from 1981 to 1987. He became actively involved in the growth of National User facilities, including Chairship of the Advanced Photon Steering Committee and participation in National Academy of Science (NAS) and Department of Energy (DOE) studies. In 1981, he joined Exxon Research and Engineering Company as Director of their Physical Sciences Laboratory. In 1984, he was appointed Senior Director of their Corporate Research Laboratory. In 1989, he was appointed Professor of Physics and Director of the Princeton Materials Institute at Princeton University. He is currently a Professor of Earth and Environmental Sciences at Columbia University, where form 1996 to 1999 he held the posts of Vice Provost of the Earth Institute of Columbia University and Director of Lamont-Doherty Earth Observatory of Columbia University. Dr. Eisenberger is a fellow of both the American Physical Society and the American Association for the Advancement of Science. Dr. Eisenberger was one of the authors of the National Action Plan for Materials Science and Engineering, and was a member of the Commission on the Future of the National Science Foundation (NSF). He was chair of the Advisory Committee in the Mathematical and Physical Sciences Division of the NSF. His recent activities include Chairman of the Board of the Invention Factory Science Center, Member of the Board of Trustees for New Jersey's Inventors Hall of Fame, Director of Associated Institutions for Materials Science, and organizer of NSF/DOE Conferences, "Basic Research Needs for Vehicles of the Future," "Basic Research Needs for Environmentally Responsive Technologies of the Future," "Organizing for Research and Development in the 21st Century," and "Basic Research Needs to Achieve Sustainability: The Carbon Problem." More recently, he has been appointed by Governor Whitman to the New Jersey Commission on Science and Technology and Co-chair of Flandrau Science Center Senior Advisory Board at the University of Arizona.

DISCUSSION

Chairman BOEHLERT. Thank you very much, Mr. Eisenberger.

Mr. Garman, I appreciate the additional money that DOE has requested for exploratory hydrogen research in the Office of Science. That is definitely a positive step that demonstrates, I think, your responsiveness to outside guidance. You say in your testimony that you are evaluating some additional programs to see if more money should be shifted to exploratory R&D. On what basis will you make that decision and are there specific criteria?

Mr. GARMAN. This is a very iterative process, Mr. Chairman. And one of the things that we did early on is share with the Committee our draft, hydrogen fuel cell infrastructure technologies program, program plan. This enabled the Committee to interact with us in some of these areas and was the reason, I will tell you, that in the President's 2005 budget submission we did ask for $29 million in the Office of Science to do some of this more fundamental work. We—there are—and so this is going to be an iterative process. I don't think there are any hard and fast rules of thumb about precisely when and how we will shift funding.

But there is something very important that I think we need to get out on the table and understand, and it may be the basis of the Committee's misunderstanding in some of these areas. Nobody is talking about doing premature technology demonstrations. And in fact, we find this very report very useful in helping us to fend that off from those of us—or from those who are saying, some members in the other body, I might add, that we are not being aggressive enough and that we need to go more quickly to larger scale technology demonstrations, get certain numbers of cars on the road by certain target dates irrespective of whether the technology, the underlying technology, is ready. The commercial success has to be clear. The business case has to be clear.

So I think it is very important to make that point that our demonstrations, when we say demonstrations or technology validation activities, we are talking about putting a very limited number of vehicles on the road that will produce data that goes right back into the R&D process, including the exploratory R&D process. We are not talking about building large facilities. We are not talking about doing large vehicle demonstrations that are designed to drive unit costs down. We are talking about learning, very small, limited learning demonstrations that produce data that go right back into the R&D process. So there is a lot of agreement on this panel on that subject, and I think that it is very important to make that point early on.

Chairman BOEHLERT. The development of technology should set the pace then, that is what you are saying?

Mr. GARMAN. Absolutely. You should—we should not be in a rush to deploy vehicles either in the context of a large demonstration or actually trying to force market adoption of a technology that is not ready.

Chairman BOEHLERT. Well, do you agree with these experts, then, that we need to shift some more money to exploratory research?

Mr. GARMAN. Exploratory, yes. And this is where we may have a nomenclature problem, and I want to be very careful. This program is on a razor's edge. Some would say we need to do more fundamental and basic science, and of course, we have some coming at us from the other side saying no, we need to rush to deploy the technologies we have got today, which would be a horrible mistake, because it would lock in those technologies at their current state of development. It would be premature before codes and standards and the other work that needs to be done are completed.

So we are on a razor's edge here. We don't want this to become a basic research program of the kind that government can work on for 20 or 30 years before it produces results, but we don't want this also to become an effort where we start to deploy and push before we are ready. So we are on a razor's edge.

Chairman BOEHLERT. Yeah. Yeah. And you always are very careful. I noticed that. Thank you, and I really appreciate it.

Dr. Ramage and Dr. Eisenberger, let me ask you each in order, do you think that $29 million for the Office of Science is enough for the type of program you envision? Dr. Ramage.

Dr. RAMAGE. Well, may I first tell you exactly what I think we recommended on this issue, and I think that will help me answer the question?

We recommended that there were certain areas where there needs to be increased exploratory research. Hydrogen storage is one of them, particularly in direct hydrogen production and other ones, storage is a big issue. And you know, the $29 million and the fact that that has been made, I think, is a very positive move. I can't tell you if that is the right amount of money, but I certainly think that is in the right direction.

May I make another comment, though——

Chairman BOEHLERT. Sure.

Dr. RAMAGE [continuing]. On this issue? You know, I have managed research all of my life, and the worst thing you can do in a program is have a program that has too much basic research and you don't have the right balance, which is really what my first question was. And you really need programs where you have basic research, development, and learning demonstrations so you can constantly move your technologies through the programs. And you can be testing them and learning them at the same time. And you have to make sure that in your research program you are actually working on areas where you have major gaps in knowledge, and storage is one of those areas. But there are other areas, and we argue for a transition using distributed production. That is really a development effort. And it is not—and that effort, we think, is very important, but developing a small scale, at-site reformers is effort that is in the development and there are learning activities that are required to do that.

So the answer to your question is we are very happy, and the Committee was very happy to see $29 million. But this is not an issue of basic research versus something else. There is a continuum of activities that have to take place to keep this economy moving toward a hydrogen economy. And in the end, a lot of things that we think will happen, we don't know what they are today.

Chairman BOEHLERT. Dr. Eisenberger.

Dr. EISENBERGER. In answering the question, let me try to put this in a frame, which I think is contributing to part of the confusion. Let us say when President Kennedy committed us to go to the moon, he had just the need to accomplish the task. He didn't have to worry about—our country didn't have to worry about the cost or consumer acceptance of the particular way we went. And what we have here is a concatenation of both a national security need and a market need. And we are mixing up, in some cases, the drivers that would make one want to regard this as a national security objective with the way you would prudently address something that ultimately the consumer has to accept. And as much as the national security wants it, if the consumer doesn't accept it, it ain't going to happen. And I think it is in trying to understand which track we are on and keeping for sure that we know in the bottom line we have to be on the consumer track that would help us all stay on the same path.

So I agree with the philosophy stated here in terms of the need to have this continuum, but my concern is viewing it as something that ultimately has to make the—meet the market. It is something that we would normally—I—my instincts, my judgment, I can't give you a number, because I would have to spend a lot more time to look into it, but I feel that we are putting too much of the resources downstream, right in that continuum that Dr. Ramage talked about, and not enough upstream, and that since the amount of money that goes into demonstration projects, in industry you know once you course the demonstration projects, they are the ones that cost you a lot of money. All right. They are very expensive. A $1 billion research program is unimaginable, right? We are talking about millions, but the demonstration projects are much more costly. So I would say notionally, I—there is a need to shift more. I couldn't give you a number. All right. But I can say that I think there is this confusion between whether we are doing this ultimately that it has to meet the marketplace or we are doing it because of national security.

Chairman BOEHLERT. Secretary Garman wants to——

Mr. GARMAN. And there is just—again, there is—I think there is a miscommunication going on here, so I want to try to correct it before it goes on too far. The $29 million in the science budget, that is what we are calling basic. That does—we are doing much more exploratory research and plan to do more exploratory research. And I think I was negligent in failing to—partly for reasons of time, to answer the five Committee questions. But one of those five Committee questions is on point when you say, you know, using the definitions in OMB circular A–11, what is your split in the current funding profile between these different types of research? In basic research, we are around 13 percent; applied research, which includes a component of exploratory R&D, about 42.5 percent; development, 29.2 percent; demonstration, 13.4 percent, and that constitutes what we have. And the only deployment work we are doing is a tiny two percent, mainly related to education for the very long-term.

Chairman BOEHLERT. Thank you for that clarification.

Mr. Larson.

Mr. LARSON. Thank you. Thank you, Mr. Chairman. And I thank the panelists for being here for your—and for your fine testimony. And I thank the Chairman again for this hearing that is important to each and every one of us. It is rarely an opportunity in my years in government that you get to talk about a subject matter that embraces energy, the economy, the environment, and foreign policy all in one breath. And so I think the dynamic here is extraordinarily important, but never has there been such a great need, and in my estimation, so little funding toward that effort. And I think the hard truth is that if we are going to aggressively pursue a hydrogen economy, then we have got to aggressively put forward the funding that we are going to need. And I say that lauding the Administration in terms of the efforts it has made to date, but recognizing that even though these efforts are well intended, it is not nearly the amount of money that I believe is going to be necessitated if we are serious, in fact, about a number of the issues that you have raised and a number of the goals that the Committee has stressed to date.

A couple of questions that I have, and I am wondering with respect to—Mr. Garman, with respect to this study and the work of—and your work whether or not there has been any coordination with the Department of Defense which already has put forward close to $50 million in studies and in actual projects.

Mr. GARMAN. Yes, sir. We have worked with the Department of Defense both in the context of the stationary fuel cell work that they do, and we also interfaced with the Department of Defense in a program that we call Future Truck, which is looking at larger, heavier transportation. We have done some fuel cell work with them in that context and will continue to do so. It is very, very important. Their needs are sometimes a little different than ours, but we think there are a lot of avenues for collaboration, and we want to do even more.

Mr. LARSON. One of those collaborations I believe, and I would be interested in the panelists' views on this, is when you are talking about pilots, it seems to me that as a mode of transportation that, and you have all pointed out some of the problematic concerns raised in looking at individual vehicles, but when you talk about heavyweight vehicles, you mentioned trucks, I would focus on buses, primarily because of the mode of transportation, the fact that they are usually barned that even, the fact that they usually can accommodate some of the storage issues that were—that have been raised. And also, in terms of pure pilots and testing, seeing that this ought to be a clear focus of Department of Energy and Transportation. Would you respond, all of the panelists?

Dr. EISENBERGER. I think it makes—I would also like to echo in that regard to what Dr. Ramage said. You can't go from nothing to something. You have got to find ways to ease yourself into the market to get on the learning curve, to get things—some value out of it so that provides an economic motivation for your infrastructure to develop. And I have thought about it recently——

Mr. LARSON. That is a good point. And all of you have mentioned this with respect to the market, but isn't it also true that if we look out at our municipalities, as we look out at our states, as we look at our various schools that every single one of those schools has to transport kids back and forth to school via bus. Those plants and facilities all have to be heated and cooled. They are part of the marketplace, to be sure, but they are also part of a larger laboratory of government where, I believe, that we ought to spend a lot of our focus and emphasis, understanding that it is not the same as the commercial market. And in fact, as all of you have pointed out, we don't want to prematurely rush in areas that will be failings while we have the opportunity governmentally and in controlled pilots to take a look at these areas.

Dr. EISENBERGER. I just want to say one more thing, and then—as the Academy report said, and we also agree, that, for example, in addition to buses, distributed power gives you another way to get into this market. It gives you a way of dealing with fuel cells, providing an incentive to grow your production facilities.

Mr. LARSON. How much money is needed in bridge technology?

Dr. EISENBERGER. Well, to make a quantitative statement, one would really have to go into the details.

Mr. LARSON. Hypothetically, nothing that I would hold your feet to the fire about, but——

Dr. EISENBERGER. No.

Mr. LARSON [continuing]. Just give us some parameters. Is it bigger than a breadbasket?

Dr. EISENBERGER. Well——

Mr. LARSON. And this is the frustration on the part of Members, I think——

Dr. EISENBERGER. Right.

Mr. LARSON [continuing]. Is that in earnest, Members and this Chairman has been exceptional, want to help, but want to get realistic figures, because I think, both from a substantive and academic standpoint, the—in this case, I think the ends does justify the means.

Dr. EISENBERGER. Well, let me put—let me say it this way. I really agree very much with your comments that energy is so critical to what we do that to underfund it, to not give more resources, in general, to develop our options for our future and be able to pursue the bus idea that you made, distributed power, all right, is really, I think, penny-wise and pound-foolish in the long-term. And because it is a major issue, this—the whole future of success of, as you pointed out, all of these things coming together here, requires, really, a very significant investment. And to some extent, we are underwhelming the problem. And I—my sympathy goes to Mr. Garman who has to manage a project where he has these great objectives and he is given not all of the resources to accomplish them.

Mr. LARSON. Believe me, our sympathies go to him, too. And it may not sound that, but I know—we know the difficult task that he is operating on.

Dr. EISENBERGER. Right.

Mr. LARSON. And Dr. Ramage.

Dr. RAMAGE. Yes. Just specifically on the buses, I—our Committee felt very strong that in the early part of the transition to a hydrogen economy that the—you would actually use fleets, buses and other things, and you could use existing production capacity, so you don't have to worry about the infrastructure, and there is hydrogen out there, and you basically would do it. And that would allow you to enter the market with fleets, and buses would be a big part of that. And that allows you to move forward while you are doing your R&D program. It allows you to get commercial use. It allows consumers to get use. You get learning demonstrations. So, in our vision, that literally is the first part of this transition. Later on, you would have distributed production at sites when vehicles come in the market. But the buses and mass transportation would be the first part of this.

Mr. LARSON. What about the transmission? And I noticed in your comments, and I really do appreciate the talk about making the transition with coal and other entities, you didn't mention natural gas, which I would think, from a distribution standpoint and pipeline standpoint and transmission standpoint, might be critical to the future, although we note that that is a limited source as well.

Dr. RAMAGE. Well, the—our issues on natural gas are we believe that during the transition, natural gas should be a primary source of hydrogen, but in the steady state, unless we have some major natural gas findings in this country. If you look at EIA and the amount of natural gas that we are importing, it becomes the same national energy security issue as oil. And so we separated and basically recommended that the DOE make—decrease the size of their program in large-scale natural gas, focus on using natural gas during the transition for small-scale reformers.

Mr. LARSON. How far away are we with coal and making that—in being able to capture the hydrogen from that process?

Dr. RAMAGE. I think you are probably—I mean in a coal plant, like the parameters in our future, are 15 or 20 years away. So it is a—coal is a long-term part of the steady state solution.

Chairman BOEHLERT. The gentleman's time has expired. The Chair recognizes the Chairman of the Subcommittee on Environment, Technology, and Standards, a distinguished fellow of the American Physical Society, Dr. Ehlers.

Mr. EHLERS. Thank you, Mr. Chairman. And I am very pleased to have another physicist at the table. And thank both of you for your work in this extremely difficult project. You have done a good job of identifying the problems, and I am—in my analysis of it, which incidentally is far less extensive than yours, but agrees with yours, there are so many different things that have to happen simultaneously. And it has to be an incredible governmental/industry cooperation to achieve the results that we want. Such simple matters as deciding how is—well, you mentioned fuel storage in your study. It is not just storing it underground somewhere, but how are you going to store it in the car, because that influences the service stations of the future? Are you going to get in—go in and get a tank full of liquid hydrogen? Are you going to go in and exchange high-pressure cylinders? Tremendous decisions have to be made with major impacts upon industry, and it is going to take intense cooperation to get this done in any reasonable sort of time.

In terms of the production of hydrogen, I will simply tell my colleague from Massachusetts, I personally think natural gas is too good to burn or to use for hydrogen. It is too precious as a petrochemical feed stock, and we should reserve it for that. I hope that nuclear power is an efficient way to produce hydrogen, but I haven't seen the evidence yet.

So what I really appreciate is your pointing out the complexity. It can be done, perhaps more rapidly than you say, but it is going to have to be a national crash program. And I don't—and that leads to a question for Mr. Garman on the budget. I am very concerned about DOE's budget. Last year, when you testified, you said that this program is not going to gore anyone's ox. I think this year's budget shows that maybe you aren't goring them, but you are certainly bloodying them. But also, I am very concerned that you don't seem to have much money in the budget to deal with this in terms of the problems that have to be dealt with. And I wonder if you would give us some comment on those two issues.

Mr. GARMAN. Thank you. And I——

Mr. EHLERS. It appears that other alternative energy sources are suffering, and also, you are not getting enough.

Mr. GARMAN. Thank you. And I appreciate that. And it goes also back to the Chairman's opening statement with respect to his observation or belief that it is unfortunate the Administration proposes to pay for hydrogen research by cutting the rest of Secretary Garman's programs. That hasn't happened, Mr. Chairman.

Chairman BOEHLERT. That is good news. Tell me the rest of the story.

Mr. GARMAN. I will tell you the rest of the story. Overall funding for the Office of Energy Efficiency and Renewable Energy is up. Our renewable energy program funding is up 4.8 percent. Yes, there was a reduction of 2/10 of one percent in energy efficiency funding, and there were also some shifts in that funding, but our overall budget is up, particularly when you look at the impact of congressional earmarks that are funding that is not on our R&D planning. Our wind power is up. Hydropower is up. Geothermal is up. Solar power, if you remove the earmarks of about $1.5 million, solar power is up. Biomass, if you remove the $51 million worth of earmarks in biomass that do not contribute to our program planning, the program planning that we have come together with industry, with the Department of Agriculture to devise, our biomass is up some $30 million.

Mr. EHLERS. You are beginning to sound like some radio announcer giving the stock quotes for the day.

Mr. GARMAN. So, you know, I feel, actually, quite the opposite. I don't feel encumbered or savaged; I feel blessed that in a constrained budget environment, we have been given as much as we have been given. And that puts and awesome responsibility, I think, on us to perform in that context.

Chairman BOEHLERT. That you attribute to the exceptional confidence people have in you.

Mr. GARMAN. I hope so, Mr. Chairman. I hope it is something.

Mr. EHLERS. But you would not object if the Congress gives you more.

Mr. GARMAN. I think the President has submitted a very good budget, and let me say this, this is an important—and as I said before, and I know it is impolitic of me to say it in this forum, but we were saddled with $67 million worth of earmarks. I even have an earmark for hydrogen, Mr. Chairman, that doesn't have anything to do with hydrogen.

Mr. EHLERS. Okay. We will try and take care of that this year.

A quick question, Dr. Eisenberger. On the APS report, you talked about the storage problems. Could you give a quick rundown what you see those to be and what you think the most likely choice is going to be?

Dr. EISENBERGER. Well, you know, it is no accident we are running on gasoline, because it is a very unique fuel in terms of its capability in terms of energy density and ability to store in the automobile the amount of energy you need to travel what the consumer has learned to understand they can expect. I just turns out that currently hydrogen, given its basic properties, you can squeeze it, you can do various things to it, it is extremely difficult to, currently, have a material where you can imagine getting enough energy density in the automobile in a way that is safe so that you can give the sort of performance that the consumer has learned to—or that the transportation sector needs. And so right now, there is not a known answer to this. And so that is a gap that is a really serious problem. Now what I would say is, and it gets back to your comment and it is a thing that concerns us as well, to make this thing work, it is no better than the weakest link in the chain, right. You can't get there if—because it is a consumer-oriented thing, if something doesn't work. And it is that—the magnitude and the complexity that suggests to us that this idea of piloting, and I don't want to—and I agree that there is verbiage here that we could clean up, but piloting things that are ready to be piloted and then focusing very clearly on those gaps which really are serious in terms of not having, as Dr. Ramage said, even a commercial performance demonstration yet, that one has to make sure that one really focuses on those things, because one knows one can't go to market until one gets those things addressed.

Mr. EHLERS. Right.

Chairman BOEHLERT. The gentleman's time has expired.

Mr. Costello.

Mr. COSTELLO. Mr. Chairman, thank you.

Mr. Garman, I want to ask you a few questions about the FutureGen program. The Administration has made it very clear that it is the important program for this Administration. And when George Ruddins testified before our Committee, I think it was in November of 2003, he provided a tentative timeline for the FutureGen project. And you know, in the fiscal year 2004 appropriations bill, DOE was directed to produce a program plan for the FutureGen project by December 31 of 2003, and I am wondering what the status of the plan is.

Mr. GARMAN. I made sure we spoke to George right before I came up, and the program plan, which was promised to you, is in the final review process within the Administration. And I am told it will be transmitted to Congress shortly. And we hope to have that up to you as quickly as possible. That brings to mind the fact that I have promised this committee a hydrogen posture plan, which I produce right now. *[The information referred to appears in Appendix 2: Additional Material for the Record.]* I have done that. And I will have George follow up with your staff, but it is out of the building. It is out of DOE and undergoing interagency concurrence at the White House, I am told.

Mr. COSTELLO. When you indicate that it will be delivered to the Congress shortly, could you get a time frame on there, 30, 60, or 90 days?

Mr. GARMAN. I would hope it would be within a week or two.

Mr. COSTELLO. Let me ask another question about FutureGen and about funding for the project. The coal R&D budget provides $237 million of previously appropriated funding specifically for FutureGen. There are $233 million of new funding available for other coal R&D programs, which is almost a 50 percent cut in programs like fuel cell research, coal gasification, advanced research centers, and other important programs compared to last year. And as, I think, we all realize that FutureGen is not a replacement for these programs. And in fact, if anything, the program, FutureGen, can not succeed without them as a foundation. So I am wondering if you will address that issue. How do we expect FutureGen to be successful if, in fact, we are cutting the R&D funds for the other items that I have just mentioned?

Mr. GARMAN. I would hope that the program plan would elucidate that for you. I am told that the project timeline for FutureGen remains on track for a fiscal year 2004 start and that there have been some changes in some of the out-year milestones consistent with assuring, and this may seem ironic in this context, but that some of the underlying science matches up well with the deliverables in the project. So that, since I am the energy efficiency and renewable energy guy and not the fossil guy, you have delved to about the limits of my knowledge on that specific point, but we will try to answer better than that for the record.

[The information follows:]

INSERT FOR THE RECORD

FutureGen Funding and Funding for Other Coal R&D Programs

The funding profile for FutureGen is complementary to and consistent with the Department's Coal R&D roadmap in key areas, as reported in the March 04, 2004 *FutureGen Report to Congress.* The schedule for the FutureGen project will allow the FutureGen industrial consortium sufficient time to assess the technical readiness of candidate technologies for inclusion in the FutureGen research project. The pace of the research being pursued should provide the opportunity to choose the technology best suited to meet the FutureGen project goals. Progress in the ongoing coal research, development, and demonstration program will provide the necessary technical foundation to help make FutureGen a success.

Mr. COSTELLO. The last question about FutureGen, and I realize you may not be the person to answer this, is where does the Administration with finding a partner in the private sector as anticipated and directed in this legislation?

Mr. GARMAN. My notion is that we are finding many partners and a great deal of interest, not only in the domestic private sector, but also internationally through the Carbon Sequestration Leadership Forum. There has been a tremendous amount of interest from other nations, including Germany and Poland, in partnering with us and making FutureGen the first demonstration, hydrogen-producing, zero-emission coal plant in the world to enable that technology transfer to be universally adopted around the world and that the interest is there.

Mr. COSTELLO. They—have they mentioned that they will bring their checkbooks with them to participate?

Mr. GARMAN. That is—it is well understood that that is part of the deal.

Mr. COSTELLO. Mr. Chairman, thank you.

Chairman BOEHLERT. Thank you very much, Mr. Costello. I love the international cooperation where we do all of the work and they get all of the benefit without any of the burden of helping to finance it, so that is something—that is a question we are all interested in hearing the right answer to, and you gave the right one.

Mr. Gutknecht.

Mr. GUTKNECHT. Thank you, Mr. Chairman.

I have a keen interest in this, because I also am the chair of a Subcommittee in the Agriculture Committee that deals with renewable fuels. And so we appreciate the opportunity to have you here today, and we are going to continue to look at this.

First, and this you don't have to answer right now, but I would like to get a list of those earmarks from last year. That is problematic, I think. You know, historically, this committee has done a pretty good job of not recommending earmarks within NSF or other science research projects, and it seems to me we ought to try to apply that as well to the Department of Energy.

Second, though, and I think this is a—also a very important issue, I want to raise the issue of collaboration with our universities. You know, we have a lot of pretty smart people and curious students and very good graduate students who could be extremely helpful in doing some of this research. And I guess the question is what portion of the Department of Energy's awards are directed toward university research to help develop some of these new technologies?

Mr. GARMAN. Let me answer—I will give you a precise number for the record, but let me answer it this way, because it bears on a question asked earlier about the challenge of hydrogen storage on board the vehicle. And we fully appreciate, understand, and agree with that challenge. And in fact, this is one of the areas where the Academy, in its report, actually commended our hydrogen storage initiative as "a strong program with the right balance of basic research". And the reason I mention that is because it is our plan, in fact, we will, in a matter of days, be announcing winners of a hydrogen storage solicitation, which we have had on the street, composed of teams of universities and national labs. We thought it was so important that we make sure that the university component is included in this for a variety of reasons. First of all, it helps us make sure that there is the basic research component. Second, it avails you of that opportunity to take advantage of research at universities that can often be produced at a much lower cost than research at national labs because of the availability of graduate students and all of the other good things you have in universities. So——

Mr. GUTKNECHT. Cheap labor.

Mr. GARMAN [continuing]. We are very much looking forward to the opportunity to make that solicitation, get more universities involved in this fundamental research on one of the most, we agree, vexing problems that we have in making this initiative a reality.

Not to beat this dead horse, we will probably have to delay the actual funding a little bit, because of the impact of the earmarks, but we are going to go ahead and make the selections, let the people know they have—they will be awarded these things just as soon as we can scrape up the funding and get it out to them.

Mr. GUTKNECHT. The next question, and perhaps either Dr. Ramage or Dr. Eisenberger can jump in on this, and I think this is something I am keenly interested in, and that is using renewable energy sources, such as biomass or wind or other sources like that, to actually produce hydrogen. To what extent should our hydrogen-related efforts focus on deriving that hydrogen from some of these renewable sources? And let me give you an example. I mean, we have—there has been just an explosion of the latest and most efficient windmills in my District. I am amazed, with the modest amount of incentive from the Federal Government, we have seen just an explosion. Now in some respects, there is at least discussion out there about using those, when we don't need the power on the grid, to produce some other energy source, which could be storable. And hydrogen might make some sense. I would like to get your particular—particularly Dr. Ramage or Dr. Eisenberger, your particular point of view on that.

Dr. RAMAGE. I think it is a very good question. And we strongly recommend in our report that wind energy play a major role in the transition and maybe in the steady state, and it is because wind energy today, in a lot of areas, has almost—is almost cost-competitive with grid electricity. And also, there has been a lot of—there is a lot of activity going on in industry to look at ways to improve it more.

The second piece of this, and that is that we believe that electrolyzers, which are now a big component in generating hydrogen, will end up coming down greatly in cost. And so marrying wind energy with advances in electrolyzers will play a major role, probably, you know, in the early parts of the transition to generate hydrogen.

With respect to the question about—you know, we recommend that biomass not be used directly for gasification as a source of hydrogen. It doesn't mean we don't think that biological processes are important. That is more of a fundamental research. But just looking at hydrogen, there is a lot of land required. In our report, we identify that, in fact, to use biomass to generate the hydrogen would take about half of the cropland in the United States. And it is just not a very efficient process. While it might be important if there are limited funds in the DOE, we believe that effort should be focused more on exploratory ways to look at—directly at biological means. We do fully support solar energy as a method to produce hydrogen, particularly direct—but wind is a very important key component, we think, in the transition. And the technology is ready. It is close.

Dr. EISENBERGER. My comments are along a similar line, but maybe I will try to take a slightly different cut at it. Part of the message I have tried to communicate is that in the understandable pressure in the short-term to try to come up with solutions to mitigate our dependence on foreign sources of energy and to deal with issues—environmental issues, we should recognize that the—in the long-term, there is no alternative but to find a solution that has some renewable energy source, some way of converting it into a storable fuel that can be used in various ways to meet our energy needs. That is the end game. There is no getting away from that. It is a matter of time. And some at some level, our concern has been that we need to balance that understanding of where you are going in the long-term, and then each step of the way make sure you don't over-commit your resources in things that are not going to get you there, and in the process of doing that, I mean I agree with everybody, like Dr. Ramage said, you can't ensure success. There are going to be failures, but we know in America what America does to failures: you leave it and then you don't talk about it for another 10 or 15 years. And so part of our concern is that if we focus too much on the short-term and try to commit to things that won't give what we expect from them and don't really solve the long-term problems that we have to face, we could set back the overall initiative. So being prudent is not because we don't believe hydrogen has a place to—a role to play, but our prudence is actually concerned that if we move—get too far ahead of ourselves, we will hurt where we all know where we have to go.

Chairman BOEHLERT. Thank you very much. The gentleman's time has expired.

Mr. Akin.

Mr. AKIN. Thank you, Mr. Chairman.

And Mr. Garman, I just wanted to appreciate just publicly that you came to our District, and there is a lot of interest and enthusiasm as a result of your stopping out and chatting.

My question is a pretty fundamental one, and I guess it might be appropriate for Dr. Eisenberger. I guess the concern I have sitting here, the more I have listened the more I feel like I am about like a bottle of champagne, it seems like what we are doing is we are putting some sort of emphasis on hydrogen. It seems to be almost dictating the solution. We haven't defined what the problem is. It would be a little bit like if we are trying to get across a river, and I would commission you guys to work on suspension bridges. You know, well, maybe there is another way to build a bridge than a suspension bridge. It seems like here that is what precisely are we trying to do. And the big thing that I ask myself in hydrogen is as people talk about it, it is not like you can grab yourself by the bootstraps and fly around the room. There is some source of energy. It is either going to be—I mean, you can do it on the margin. You can do something with some solar and some wind and stuff, but when you look at the volume of energy that there is going to be, and that demand is only going to go up as nations become more industrial. You know, you have got basically nuclear, you have got coal, and you have got oil. Those are your big ones. And hydrogen doesn't change that equation. So I guess my question is aren't we putting the cart way before the horse? And shouldn't we be really addressing specifically what are the problems? Is it foreign oil? Okay. How do we deal with that? Is it emissions in cars today? Then how big a problem is that, and how do we deal with that? It seems like we are going completely backwards. What we should be doing is just specifically saying this is the problem, this is the goal, and now what technologies are available? Am I off the track? Or will you just please respond.

Dr. EISENBERGER. I will—you know, it is unusual to hear a politician describing an idealistic approach to a problem, right, but I agree with you that conceptually that is the way one should go about this problem. And that—but on the other hand, I would also say, as a pragmatist, that energy is so critical to our society that there is not one single answer. All right. And we have an interest in moving in hydrogen. You know. Forces have come together, as was mentioned in the introduction, where there is support from many sectors to advance this technology. It has a role to play. It is not the only answer, as I tried to say. We need other things as well. And we should not—we should be investing more in alternatives, and if we would do that, then we could take your approach. If we had a real commitment to say, look, we are going to solve, as you pointed out, the security aspects of it, the environmental aspects of it, then we could sit down and have a program that would be a lot more expensive than the program we are now committed to. It would require more options and more different directions than we are now pursuing.

Mr. AKIN. I—just one other—I promised I would try and get one of these. These are the, you know, questions distributed ahead of time that, you know, you have to—but this is a good question. And this is the first page of the NAS executive summary states: "DOE should keep a balanced portfolio of R&D efforts and continue to explore energy supply and demand alternatives that do not depend on hydrogen. If battery technology improved dramatically, for example, all electric vehicles might become the preferred alternative, however, EERE funding for battery and electric vehicle technology has been drastically reduced over the last few years." Based on the NAS statement, might you increase funding for battery or non-fuel cell vehicle technology research?

Dr. EISENBERGER. That is along same lines as what I was saying before. You have got a problem, whoever wants to—and Dr. Garman—I mean, Mr. Garman, if you wanted to respond, that——

Mr. GARMAN. I thank you for that question, because once again, it gives me the opportunity to correct. Our hybrid and electric propulsion vehicle program budget funding line is not down. It is up. We are not investing all of our eggs in the hydrogen basket. We are spending more on hybrid technology and energy storage technology. That is batteries. We think there is great promise in lithium ion batteries, and we think that is a very important technology. And the reason that it is such a good bet for us to be investing in those technologies is not only will those be used in fuel cell vehicles when they come to pass, but they could also be used in the interim. And so this is a no-brainer. We——

Mr. AKIN. You are disagreeing with the premise.

Mr. GARMAN. I am disagreeing with the premise——

Mr. AKIN. You are saying—okay.

Mr. GARMAN [continuing]. Of the question. Yes, sir.

Mr. AKIN. All right. Thank you very much. Anybody else? I have got another two seconds left.

[No response.]

Mr. AKIN. No? Thank you. Thank you, Mr. Chairman.

Chairman BOEHLERT. Thank you very much.
Ms. Biggert.
Ms. BIGGERT. Thank you, Mr. Chairman.
Mr. Garman, a central theme of both reports is that there are hard technical problems that require basic research to solve. And I think both reports are clear in recommending that funding be shifted away from product development in large-scale demonstrations toward exploratory, fundamental research. And I was pleased to see that the Office of Science was included in the Initiative with $29 million in new and reallocated funding. Do you agree with the reports that more basic and fundamental research is needed to meet the goals of the Initiative? And while the funds of—for science is a good first step, is the Department planning any future increases in basic research?
Mr. GARMAN. I think the key, and I will leave it to the—to Dr. Ramage to correct me if I am wrong, but first of all, on the issue of demonstrations, we are not proposing to do large-scale demonstrations at this time. We don't think it is ready. We have not proposed that. We have proposed to do very small-scale, learning demonstrations where we have vehicles, not in the millions, not in the hundreds of thousands, but in the tens, tens of vehicles to produce data and information that feeds back into the R&D process.
Secondly, yes, we do agree with the proposition that there needs to be more basic and exploratory research. And as you noted in our fiscal year 2005 budget submission, we have involved the Office of Science in this work, and we are also—you will be seeing us doing more exploratory research in our research that we are doing as well above and beyond that $29 million. So we concur with the recommendations in the report.
Ms. BIGGERT. Thank you.
Then, Mr. Garman, again, we know that it is possible to produce a car that gets 50 miles or more to the gallon. And in fact, there are a few on the market today, such as the Toyota Prius. Rumor has it that you drive one?
Mr. GARMAN. I bought two, in fact.
Ms. BIGGERT. Okay. Well, thinking of one in the APS report shows in energy information Administration projection of the U.S. demand for imported oil increasing steadily while U.S. production is flat, producing a need for 16 million barrels per day of imports. And the same graph shows that a fuel economy of 39 miles per gallon, only about ¾ as efficient as the Prius, would save about five million barrels per day. But the fiscal year budget request for the hydrogen program has a goal of only 1/10 of one million barrels per day in 2020. And why are we cutting programs? I think you just said we were not cutting programs, if that is true.
Mr. GARMAN. We are not. And in fact, we are enthusiastic supporters of hybrid vehicles. The President has requested the passage of a tax credit for purchases of hybrid vehicles, which is in the energy bill, awaiting passage. He proposed that in May of 2001 with the issuance of his National Energy Plan. So we believe very strongly that hybrids are a wonderful bridge technology and even more so because some of those same hybrid technologies, the power electronics, the energy storage, the electric drive, will also be incor-

porated in the fuel cell vehicles of the future. So we are—on this graph, which you point out in the APS report, I think it is important to point out that that graph came from our office. And I think that even—the thing that is interesting to me is even if you have an immediate 60 percent increase in corporate average fuel economy standards and a much smaller increase was resoundingly defeated in the other body by a wide bipartisan margin, I have to point out, that curve still starts going up after a certain point in time. Yes, it does save oil, but it does not get us on that pathway of eventually delinking light-duty transportation and oil use. And Representative Akin really asked the million-dollar question: What are we doing this for? And the answer is quite simple: we are doing this to eliminate and delink light-duty transportation from petroleum use. The great thing about hydrogen is it is not an energy source; it is an energy carrier. And we can produce it from coal and nuclear and renewable energy and a lot of other things we have here. Because as this committee has pointed out, we don't have a lot of oil. We have two percent of the world's proven reserves, and the Persian Gulf nations have 64 percent. So we are doing this to get off of imported petroleum. We are also doing this to eliminate emissions of all kinds at the tailpipe and delink light-duty transportation from oil use. It is that simple.

Chairman BOEHLERT. Thank you very much. The gentlelady's time has expired.

Ms. BIGGERT. Mr. Chairman, I have one more question. Could I submit it and ask that I get a response?

Chairman BOEHLERT. By all means, all Members will have the opportunity to submit questions in writing to our witnesses, and we would appreciate timely responses.

The Chair is now pleased to recognize the distinguished Chairman of the Subcommittee on Space and Aeronautics, who is fresh from an overwhelming victory at the polls in California just yesterday, Mr. Rohrabacher.

Mr. ROHRABACHER. Yes, that is why I am the distinguished instead of the extinguished chairman.

I would be happy to yield to Ms. Biggert for—to let her ask her question. Go right ahead. You only have two minutes.

Ms. BIGGERT. Thank you very much, Mr. Chairman.

This is for Dr. Ramage. One of the recommendations from your report is a greater emphasis on fundamental research on photosynthetic microbial systems. And my understanding is that the Office of Science Environmental Genome program is getting promising results as it examines hydrogen-producing microbes. Would you—could you expand a little bit on your recommendation and tell us more about the potential of the environmental genomics?

Dr. RAMAGE. I am not sure. Let me—could I make a comment about why we recommended focusing directly on hydrogen production? If you think about most renewables make electricity, and when you make electricity with a premium fuel and you have to convert it to hydrogen, which is a commodity fuel, you are losing energy, and you spend money. And that led us, by looking at costs, the recommendation to look for ways directly in order to make hydrogen from biological and solar methods. There has obviously been a lot of progress made in genomics and metabolic type of activities in general and the ability to design organisms that can actually produce hydrogen has been increasing a lot. There is still a long way to go, but our Committee strongly felt that that is where a lot of the exploratory money should go and go away from, you know, traditional biomass, because there has been a lot of progress made.

Ms. BIGGERT. Thank you. Thank you.

Mr. ROHRABACHER. All right. Well, let us see here. Just one note before I ask my question. I have been a Member of this committee long enough to remember the Partnership for a New Generation of Vehicles program, the PNGV. Do we all remember that? We spent about $1 billion in that, and then we just sort of walked away. And there was $1 billion that evaporated. I just hope that this isn't one of those types of things where there are a lot of press conferences and a lot of verbiage and then just nothing to show for the money that has been spent.

And speaking of spending the money, I would—from the testimony, I understand that we don't even have a tank designed now for the automobile that could actually have hydrogen and use it as a hydrogen storage supply system that would then power the car. How much money is going into finding and designing one of those in the budget that you are asking for right now?

Mr. GARMAN. We actually do have a tank, and the hydrogen fuel cell vehicles that are on the road in California and other place do carry hydrogen on board the vehicle, unfortunately, not enough, about the range of 150 to 175 miles.

Mr. ROHRABACHER. Right.

Mr. GARMAN. And we need a 300-mile range or better.

Mr. ROHRABACHER. Okay. So how much are we spending on trying to develop that tank out of the money that is being—you are asking for this year?

Mr. GARMAN. Our overall storage initiative is earmarked at about $150 million over five years.

Mr. ROHRABACHER. $150 million over five years?

Mr. GARMAN. Yes, sir, around $30 million a year.

Mr. ROHRABACHER. Boy, that is a lot of money to design a storage tank.

Mr. GARMAN. Well——

Mr. ROHRABACHER. $150 million——

Mr. GARMAN [continuing]. If I can explain why, it is—what we are doing is looking at completely new materials——

Mr. ROHRABACHER. All right.

Mr. GARMAN [continuing]. Including chemical hydrides, metal hydrides, allenates, carbon nanotubes, other more esoteric storage materials that can be used to store that hydrogen at near ambient temperatures and pressures. Today, the kind of hydrogen tank on board the vehicle is a 5,000 or 10,000 p.s.i. tank of compressed hydrogen. We think—and of course, cylindrical tanks are very bulky; they take up a lot of space on the vehicle. They cost a lot of money. So we are trying to come up with new designs in partnership with the private sector that can create a tank that will meet those performance standards——

Mr. ROHRABACHER. So there is no material that exists today that could be used to construct a hydrogen fuel tank that can meet the consumer benchmark?

Mr. GARMAN. That is correct, that meets——

Mr. ROHRABACHER. As of right now?

Mr. GARMAN [continuing]. Our cost targets. That is correct.

Mr. ROHRABACHER. So you are having to go straight to, you know, really fundamental science on this, and you are going to spend $150 million on that, and this is a—could I say it is a shot in the dark, because you don't really know if you are going to find it or not?

Mr. GARMAN. I would say that it is—this is the one area, the primary area where we think we do need a technological breakthrough in order to meet that consumer demand.

Mr. ROHRABACHER. Okay. There is no technological breakthrough needed to make this fiscally responsible in terms of what type of fuel you will be using in order to create the hydrogen for fuel in the first place? That is not a—you don't—that is already decided in a——

Mr. GARMAN. No, sir. I think the—again, the beauty of hydrogen is that you have a variety of different primary energy sources that you can use to make the hydrogen fuel. I think the early years, as it has been pointed out, that is most likely to be natural gas distributed at the station. And we believe we can meet that target with, you know, $1.50 per gallon of gas equivalent hydrogen, or $1.50 per kilogram by 2010.

Mr. ROHRABACHER. That is a pretty good——

Chairman BOEHLERT. The gentleman's time has expired.

That is a pretty good goal. Come up to the State of New York where the gasoline price is considerably higher.

The Chairman now recognizes Dr. Burgess.

Dr. BURGESS. Thank you, Mr. Chairman.

And actually, I am very relieved to hear that there is not being any diversion of funds from the hybrid system, because, like you, Mr. Garman, I believe very much in that technology. And in fact, I went out in January to buy a Prius, and in my part of the world, you can't buy one, and I guess that is because you bought two, so I wanted to make a note of that.

The—and you have answered this question already, but I will go ahead and ask it, because it hasn't specifically been answered, but the idea of getting our hydrogen from natural gas, our—and I do recognize that there are other sources, and I am very glad to hear you talk about solar and wind sources for generating hydrogen in the future, but in the short-term, are we trading our dependence on foreign oil for our dependence on foreign natural gas?

Mr. GARMAN. We—you have given me an opportunity—a very interesting point that I think has been lost. And we are, today, producing nine million metric tons of hydrogen each and every year from natural gas. We make a lot of hydrogen in this country, mainly for use at refineries and other locations for desulfurization of gasoline and diesel products. We would—if we wanted to fund our—or fuel our entire fleet using natural gas, we would need around 53 million metric tons, which is, you know, not a huge factor above that that we are already producing today. Now I—but I agree with the fundamental premise. We want to be careful. We do not want to trade a dependence on oil for a dependence on natural gas that has to be imported, which is why I think the point of the

Academy is right on when they say plan for the transition period when you expect to be using natural gas, but do the fundamental work that provides the breakthrough in the other sources of hydrogen so that they can come on line soon after that point.

Dr. BURGESS. Mr. Chairman—I thank you very much.

Mr. Chairman, I would just add that the work that this committee did on the nanotechnology bill last year, perhaps, can give rise to the technological breakthrough that they were asking for with the carbon nanotubes and the reinforced carbon concept that now is the leading edge of the wing of the Space Shuttle, which may someday come to the point where you could use it as your tank.

Until we get to the point where we are making hydrogen from some other source, I look forward to seeing some hydrogen wells drilled in West Denton County. I would like that.

Chairman BOEHLERT. Dr. Burgess, I just—thanks for bringing the National Nanotechnology Initiative up.

And I would like to thank our witnesses. Let the record show that as Dr. Burgess was making his commentary, all of the witnesses nodded in the affirmative. So they are in agreement with him and talking about the good work of this committee.

And I thank you very much. Do you have anything more?

[No response.]

Chairman BOEHLERT. Just one final question as we wrap this up. I think we have reached a consensus. And how do you—how will you evaluate, Dr. Ramage and Dr. Eisenberger, if they at—Secretary Garman and his people have taken your recommendations to heart? Dr. Ramage.

Dr. RAMAGE. Well, I think that I am encouraged by what Dave has said. And I very, very—I think it was an interactive process, and I am encouraged by what he said about what the issues are, and I am also encouraged by what he said about the balance of the program and also the fact that funding hasn't been decreased in other areas.

I also know that they are moving toward developing a systems approach to managing their overall program, which is a very important part of our recommendation. So we have been very encouraged, and so I am pleased with what I have heard today.

Chairman BOEHLERT. Dr. Eisenberger.

Dr. EISENBERGER. Again, I will answer in two ways. I think that within the constraints that Dr. Garman—I mean that Mr. Garman is working under, I think he is responding. But I think the constraints should be looked at. I think that some of the questions that were asked in this hearing require that we take a look at the project in a larger context of our needs and make sure that the program is not dictated by externalities that really have very little to do with any specific objective. And there is some indication that those distortions are part of the problem that we are trying to deal with.

Chairman BOEHLERT. Thank you very much. And you have both confirmed by what you said in response to a number of questions something that the Chair has long felt, and I know Members of the Committee, who are familiar with Secretary Garman, feel that he has an extensive outreach program. He talks to people like you, but more importantly, he occasionally listens to people like you. And once in a while, he even listens to those of us in the Congress. So I want to commend you, Mr. Secretary, for the outstanding work you do. And I want to thank you for being resources for this committee, Dr. Eisenberger and Dr. Ramage. We go forward with a program that is important for America for a whole lot of the right reasons. And I feel it is in good hands. And I—but the good hands should know that we are watching.

Thank you very much. This hearing is adjourned.

[Whereupon, at 4:10 p.m., the Committee was adjourned.]

Appendix 1:

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by David Garman, Assistant Secretary, Energy Efficiency and Renewable Energy, Department of Energy

Q1. Has funding for battery and electric vehicle technology declined over the last four years? Please provide a table for historical funding level (see example below) for hybrid vehicles, for electric vehicles powered completely by batteries, and for fuel cell vehicles, indicating any overlaps of funding between vehicle types, from fiscal year 1999 to the current request. Please exclude work that applies to all vehicles such as lightweight structural materials. Please provide a total for each vehicle type as well as documenting the amount from each budget line.

SAMPLE

Fiscal Year	Budget Line	Hybrid Vehicle	Solely Battery Powered	Fuel Cell Vehicle	Applies to all
1999	Vehicle Systems – Ancillary Systems	$xxx ($yy overlap with Battery Vehicles)	$yy	$zz	$aa [should not be in other columns]
	Vehicle Systems – Simulation and Validation	$xxx ($yyy overlap with Fuel Cell Vehicles)	$zz	$aaa [overlap from hybrids plus fuel cell work]	$bb
2000	Etc.	etc	etc		
2004					

A1. Request levels for battery research and for electric-drive vehicle technology have risen over the past several years, but the research emphasis has shifted over the period, resulting in relatively more funding for hybrid and fuel cell vehicles and less for purely-electric vehicles. The following table provides summary budget data from FY 1999 through FY 2005 for work on Hybrid, Battery Electric, and Fuel Cell Vehicles.

Battery and Electric Vehicle Funding History
(dollars in millions)

Fiscal Year	Budget Line	Hybrid Vehicles ($)	Solely Battery Powered ($)	Fuel Cell Vehicles ($)	Applies to All * ($)
1999	Vehicle Systems R&D - Advanced Power Electronics				6.8
	Vehicle Systems R&D - High Power Energy Storage	12.5			
	Vehicle Systems R&D - Hybrid Propulsion Systems	22.1			
	Electric Vehicle R&D - Advanced Battery Development		5.8		
	Electric Vehicle R&D - Exploratory Technology Research		2.9		
	Transportation Materials – Automotive Propulsion Materials			0.9	0.9
	Fuel Cell R&D			32.9	
	Total Appropriation	**34.6**	**8.7**	**33.8**	**7.7**
	DOE Request	**50.0**	**11.0**	**45.6**	**6.0**
	Delta	**-15.4**	**-2.3**	**-11.8**	**+1.7**
2000	Hybrid System R&D - Advanced Power Electronics				9.5
	Hybrid System R&D - High Power Energy Storage	13.4			
	Hybrid System R&D - Light Vehicle Propulsion & Ancillary Subsystems	13.3			
	Electric Vehicle R&D - Advanced Battery Development		5.5		
	Electric Vehicle R&D - Exploratory Technology Research		3.0		
	Hybrid System R&D – Heavy Vehicle Propulsion Systems	3.8			
	Materials Technology - Automotive Propulsion Materials			0.9	0.9
	Fuel Cell R&D			36.6	
	Total Appropriation	**30.6**	**8.5**	**37.5**	**10.4**
	DOE Request	**38.8**	**11.0**	**42.4**	**10.0**

Fiscal Year	Budget Line	Hybrid Vehicles ($)	Solely Battery Powered ($)	Fuel Cell Vehicles ($)	Applies to All * ($)
	Delta	**-8.2**	**-2.5**	**-4.9**	**+0.4**
2001	Hybrid System R&D - Advanced Power Electronics				13.6
	Hybrid System R&D - High Power Energy Storage	17.5			
	Hybrid System R&D - Light Vehicle Propulsion & Ancillary Subsystems	12.5			
	Electric Vehicle R&D - Advanced Battery Development		5.6		
	Electric Vehicle R&D - Exploratory Technology Research		3.1		
	Hybrid System R&D – Heavy Vehicle Propulsion Systems	3.9			
	Materials Technology - Automotive Propulsion Materials			1.0	1.0
	Fuel Cell R&D			40.7	
	Total Appropriation	**33.9**	**8.7**	**41.7**	**14.6**
	DOE Request	**34.7**	**9.7**	**42.5**	**13.0**
	Delta	**-0.8**	**-1.0**	**-0.8**	**+1.6**
2002	Hybrid System R&D - Advanced Power Electronics				14.2
	Hybrid System R&D - High Power Energy Storage	17.3			
	Hybrid System R&D - Light Vehicle Propulsion & Ancillary Subsystems	2.8			
	Electric Vehicle R&D - Advanced Battery Development		4.4		
	Electric Vehicle R&D - Exploratory Technology Research		2.4		
	Hybrid System R&D – Heavy Vehicle Propulsion Systems	4.9			
	Materials Technology - Automotive Propulsion Materials			1.0	1.0
	Fuel Cell R&D			41.0	
	Total Appropriation	**25.0**	**6.8**	**42.0**	**15.2**
	DOE Request	**24.0**	**3.5**	**42.6**	**11.6**

Fiscal Year	Budget Line	Hybrid Vehicles ($)	Solely Battery Powered ($)	Fuel Cell Vehicles ($)	Applies to All * ($)
	Delta	**+1.0**	**+3.3**	**-0.6**	**+3.6**
2003	Hybrid System R&D - Advanced Power Electronics				13.4
	Hybrid System R&D - High Power Energy Storage	17.2			
	Hybrid System R&D - Light Vehicle Propulsion & Ancillary Subsystems	3.1			
	Electric Vehicle R&D - Advanced Battery Development		2.4		
	Electric Vehicle R&D - Exploratory Technology Research		1.9		
	Hybrid System R&D – Heavy Vehicle Propulsion Systems	3.9			
	Materials Technology - Automotive Propulsion Materials			0.7	0.7
	Fuel Cell R&D			46.2	
	Total Appropriation	**24.2**	**4.3**	**46.9**	**14.1**
	DOE Request	**28.0**	**3.4**	**50.3**	**14.0**
	Delta	**-3.8**	**+0.9**	**-3.4**	**+0.1**
2004	Vehicle Systems – Simulation & Validation				2.5
	Hybrid & Electric Propulsion – High Power Energy Storage	17.0			
	Hybrid & Electric Propulsion – Advanced Battery Development	1.1	0.3		
	Hybrid & Electric Propulsion – Exploratory Technology Research	3.3	1.1		
	Hybrid & Electric Propulsion – Advanced Power Electronics				13.2
	Hybrid & Electric Propulsion – Subsystem Integration & Development	7.9			
	Materials Technology - Automotive Propulsion Materials			0.4	0.8

Fiscal Year	Budget Line	Hybrid Vehicles ($)	Solely Battery Powered ($)	Fuel Cell Vehicles ($)	Applies to All * ($)
	Fuel Cell R&D			54.5	
	Total Appropriation	**29.3**	**1.4**	**54.9**	**16.5**
	DOE Request	**33.2**	**2.7**	**64.8**	**15.7**
	Delta	**-3.9**	**-1.3**	**-9.9**	**+0.8**
2005 Req.	Vehicle Systems – Simulation & Validation				3.5
	Hybrid & Electric Propulsion High Power – Energy Storage	17.7			
	Hybrid & Electric Propulsion – Advanced Battery Development	1.2	0.3		
	Hybrid & Electric Propulsion – Exploratory Technology Research	7.1	2.4		
	Hybrid & Electric Propulsion – Advanced Power Electronics				13.9
	Hybrid & Electric Propulsion – Subsystem Integration & Development	9.2			
	Materials Technology - Automotive Propulsion Materials				0.7
	Fuel Cell R&D			66.8	
	DOE Request	**35.2**	**2.7**	**66.8**	**18.1**
FY99 to FY04	**Total Appropriation**	**177.5**	**38.4**	**256.8**	**78.5**
	DOE Request	**208.7**	**41.3**	**288.2**	**70.3**
	Delta	**-31.2**	**-2.9**	**-31.4**	**+8.2**

* Column entitled, "Applies to All," includes work that applies to hybrid electric vehicles, pure electric vehicles, and fuel cell vehicles. Figures are rounded throughout table.

Q2. Since both hydrogen fuel cells and batteries require scientific breakthroughs, what is the technical basis for the Department's strong preference for investment in fuel cells, versus high energy density batteries, for electric vehicle propulsion?

A2. Electric vehicle (EV) propulsion battery R&D has been curtailed due to two severely limiting attributes for which no clear research solution has emerged: energy density and recharging time. The low energy density of battery technology typically limits EVs to a range of approximately 100 miles, versus the range of a conventional vehicle of 350–400 miles. The recharge time of an EV battery is up to six hours, versus the refueling time of a conventional vehicle of less than five minutes. The combination of these two negative attributes led to rejection of electric vehicles by the marketplace and by major automotive manufacturers.

The Department continues a small effort in EV batteries to address these barriers, but has shifted the majority of vehicle battery R&D to focus on the high power application required by hybrid electric vehicles, including fuel cell vehicles. Hybrid vehicles do not suffer from range limitations and recharging is conducted continually during vehicle operation. The major focus areas of this activity are use tolerance, battery life, and cost reduction.

Fuel cell technology is not inherently limited by range and refueling time in the manner batteries are. Current refueling takes less than five minutes (high pressure tank storage). Like a battery, fuel cells require two reactants, typically hydrogen and oxygen. But since fuel cells obtain oxygen from the air (essentially an infinite storage tank) the refueling and capacity of oxygen is not an issue. Therefore, the limiting factor in fuel cell vehicle range is hydrogen storage. Although our current ability to store hydrogen limits vehicle range to approximately 200 miles, this is mainly volume limited. On a weight basis, the entire fuel cell system, including hydrogen storage, has a specific energy (Wh/kg) approximately double that of today's advanced batteries.

In the spring of 2003, DOE convened a "think tank" meeting of distinguished scientists, which determined that significant promise exists in improving on the current storage capability of hydrogen: "The group believes that while the problem is challenging. . .there are materials and structures that offer promise for hydrogen storage at higher capacities." While significant improvements are required to attain a vehicle range commensurate with conventional vehicles, projects are now in place to address this issue. We recently announced approximately $150 million in hydrogen storage awards, including the initiation of three Centers of Excellence.

Q3. Please estimate the BTU's saved per federal dollar spent for Weatherization and for the Industries of the Future program.

A3. The Department understands the Committee's desire for clear cost-benefit calculations across the EERE portfolio in order to make wise funding recommendations. It is problematic, however, to compare EERE programs using a straight Btu-saved-per-dollar-invested metric. The EERE program portfolio is designed to meet a variety of National needs and provide multiple benefits not fully captured on a Btu-saved-per-dollar-invested basis. These include reducing energy bills of low-income Americans, the primary focus of the Weatherization program.

Comparisons are also complicated by differences in the composition of EERE costs across programs and in the time horizons of the expected benefits. For instance, Weatherization dollars pay for the cost of the technologies purchased, and the benefits begin to accrue immediately after installation. The Industrial Technologies Program (ITP) dollars pay mostly for research with potential benefits realized in the future.

The cost and benefit estimates discussed below are based on detailed, individual program evaluations available to date. As part of its recent restructuring, EERE continues to improve the consistency of cost/benefit measures across its program portfolio; at this point, however, EERE cannot fully compare costs or benefits of the efficiency improvements enabled by these two programs. Specifically, EERE is developing ways of estimating private sector costs, as well as more thoroughly "backing out" energy savings that would have occurred without federal assistance.

The Weatherization Assistance Program (WAP) funds energy efficiency improvements to low-income homes for Americans who lack the means of financing such capital investments. Energy price spikes can force these Americans to make painful tradeoffs between adequate heating, medical care, nutrition, and housing. Based on our most recent comprehensive analysis (conducted by Oak Ridge National Laboratory and published in 2002), Americans' energy bills are reduced by $1.30 for every dollar spent on weatherization; these savings are even greater when energy prices rise. This program also provides associated benefits that are more difficult to quantify, such as providing local building expertise, decreasing homelessness, and reducing the risk of home fires.

WAP has requested $291.2 million in the FY 2005 budget request. EERE has estimated that these dollars, in combination with leveraged funds provided by State and local utility partners will allow the program to weatherize over 200,000 homes (118,900 homes with DOE funds, and approximately 100,000 additional homes with leveraged funds). While federal dollars are projected to result in approximately 5.0 trillion Btu of source energy savings in 2005, federally-leveraged additional funding is projected to save a further 3.3 trillion Btu in source energy, for an annual total energy savings of 8.3 trillion Btu. Including leveraged energy savings, each federal WAP program dollar yields roughly 430,000 Btus in energy savings over the assumed 15-year life of these improvements.

The Industrial Technologies Program (ITP) develops, manages, and implements a balanced portfolio that addresses industry requirements throughout the technology development cycle. As opposed to the WAP, ITP's primary strategy is to invest in high-risk, high-return R&D. Investments focus on technologies and practices that will provide clear public benefit but have market barriers preventing adequate private-sector investment.

From 1977 to 2002, ITP invested approximately $2.65 billion (constant 2002 dollars) supporting research, development, and demonstration (RD&D) projects that have produced over 160 technologies. EERE estimates that the cumulative benefits of the private sector investments made in these technologies are estimated at roughly 3,700 trillion Btu, or roughly 1,400,000 Btu saved per federal dollar invested. Significant economic and environmental benefits are also achieved.

Q4. In your testimony you stated that "[W]e fully concur with 35 of those 43 recommendations. . ." from the NAS report. Which were the 35 recommendations DOE concurred with and what is DOE specifically doing to address each of them? What objections does DOE have to the other eight? Has DOE decided to reject them entirely?

A4. DOE has not explicitly rejected any of the NAS recommendations. Please refer to the attachment to this document that details the DOE response to each NAS recommendation, including the eight outstanding recommendations. The following two recommendations are examples of recommendations where DOE has not fully concurred, as further consideration is required:

- Recommendation 3–2 to discontinue PEM applied R&D for stationary systems: DOE concurs with the concept of focusing R&D to address fundamental barriers that face all fuel cell applications. However, this recommendation would have significant negative impact if not transitioned appropriately (potentially eliminating important R&D of value to both stationary and transportation applications), would send a strong negative signal to the fuel cell community and investors, would result in the loss of substantial industry cost-share, and would not allow DOE to fulfill its current obligations under several cooperative agreements. DOE feels significant discussions with its stakeholders and development of a transition plan is required before this recommendation can be implemented.
- Recommendation 3-lb to end on-board fuel processing: DOE is currently conducting a scheduled fuel processing "go/no-go" decision process, which includes input from an expert panel on the feasibility of on-board reforming. This process to examine on-board fuel processing was in place well before release of the NAS report, and DOE feels that a final decision on the NAS recommendation should not replace the formal "go/no-go" process. A public announcement on this "go/no-go" process is scheduled to be released in July 2004.

Recommendations from the Committee on Alternatives and Strategies for Future Hydrogen Production Use
Final Version (7/6/04)

Item	Priority	Rec. Number	Recommendation & Response	Issue Type: Funding	Policy	Prog Mgmt	Tech Team Charter	Technical
1	H	ES-1 and 9.1	*DOE should continue to develop its hydrogen initiative as a potential long term contributor to improving US energy security and environmental protection. Program should be reviewed and updated regularly to reflect progress, potential synergisms within the program, and interactions with other energy programs and partnerships (CaFCP). The committee recommends that DOE develop and employ a systems approach to understanding full costs, defining options, evaluating research results, and helping balance its hydrogen program for the short, medium and long terms. Such approach should be implemented for all US energy options, and not just hydrogen. DOE should map out and evaluate a transition plan consistent with developing the infrastructure and hydrogen resources necessary to support the committee's hydrogen vehicle penetration plan. DOE should estimate what levels of investment over time are required – and in which programs and project areas – in order to achieve a significant reduction in CO_2 emissions by passenger cars by mid-century.*			X		
			Input:					
			DOE Response: * The President's Hydrogen Initiative was established to significantly reduce or even eliminate our dependence on foreign oil and to improve the environment, including reduction of carbon emissions. Only through the substitution of petroleum we can solve these long-term issues. * Our interim or mid-term strategy is to reduce the use of petroleum by investing in key enabling research in technology areas such as advanced combustion regimes, lightweight materials, advanced hybrid propulsion, and high-power/energy battery development that have the potential to dramatically reduce oil consumption and environmental impact in the period prior to the widespread introduction of hybrid FCVs. These technologies also are building blocks for the hybrid FCVs. * DOE fully concurs with the systems approach and is currently establishing this capability at the National Renewable Energy Laboratory based on the NRC's interim report. * DOE will work with energy and automotive companies to discuss a transition plan consistent with the 2015 commercialization goal.					
2	H	ES-2, similar to 3-1a.	*Increased government funding on R&D dedicated to the research on breakthroughs in on-board storage systems, fuel cell costs, and in materials for durability in order to attack known inhibitors to the high volume production of fuel cell vehicles.*	X+				
			Input:					
			DOE Response: DOE fully concurs with this recommendation. In fact, storage and fuel cell costs/durability are two of HFCIT's top three research priorities with hydrogen production costs being the third.					

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3	M	ES-3a	*DOE infrastructure program requires greater emphasis and support. DOE should strive to create better linkages in large-scale and small scale hydrogen production. Hydrogen infrastructure should address issues such as storage requirements, hydrogen purity, pipeline materials, compressors, leak detection and permitting, with the objective of clarifying conditions in which large-scale and small scale hydrogen production will become competitive, complementary or independent. The committee believes that exploratory research focused on new concepts for hydrogen delivery requires additional funding.*	X+			X	
			Input:					
			DOE Response: DOE fully concurs with this recommendation. For example, a DOE/energy company technical team has been formed to address the hydrogen delivery research priorities.					
4	H	ES-3b	*DOE should accelerate work on codes and standards, and permitting, addressing the difficulties of working across existing and emerging hydrogen standards in cities, counties, states and the nation.*				X	
			Input:					
			DOE Response: DOE fully concurs with this recommendation. In fact, our FY 05 budget request is 3 times that of the FY 04 appropriation to support safety and underlying technical work on codes and standards development. In addition, DOE and industry together will address permitting issues at local levels as part of the vehicle/infrastructure "learning" demonstrations. Under the International Partnership for a Hydrogen Economy, we are working with over 15 nations and the European Union on codes and standards.					
5	M	ES-4	*DOE's policy analysis should be strengthened with respect to the hydrogen economy, and the role of government in supporting and facilitating industry investments to bring a transition to the hydrogen economy needs to be better understood.*		X			
			Input:					
			DOE Response: Technology and policy development should be coordinated. DOE believes that timing is critical in establishing policy instruments to encourage technology development. For instance, it could be premature to start offering incentives for building widespread refueling stations if the technology is not close to being market competitive or meeting customer requirements. DOE has begun preliminary analyses of key business risks related to the transition to a hydrogen economy for different points along the hydrogen value chain (production, storage and distribution, and end-use).					
6	H	ES-5	*Distributed hydrogen production systems deserve increased R&D investments by DOE. The committee believes that hydrogen economy will not develop from replacement of the fossil fuel-based economy, but due to the uncertainties in the transitional period, innovations and technological breakthroughs will be required to address costs and energy efficiency. Distributed production of hydrogen most likely will be done with small-scale natural gas reformers or electrolysis; however new concepts in distributed production could be developed over this time period, and a program should be initiated to develop new concepts in distributed hydrogen production systems.*	X+				

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			Input:					
			DOE Response: DOE fully concurs with this recommendation. In fact, a DOE/energy company technical team has been formed to address hydrogen production research priorities. We may shift more funds toward hydrogen production in future years.					
7	H	*ES-6 and 9.4*	*DOE safety program is well-planned, and should be a priority, with emphasis on* *• safety policy goals to be proposed and discussed by DOE and stakeholder groups early in the hydrogen technology development process* *• DOE should continue its work with standards development organizations to ensure increased emphasis on distributed production* *• DOE systems analysis should include safety as an overriding criterion* *• The Goal of the physical testing program should be to resolve safety issues in advance of commercial use* *• DOE's public education program should continue to focus on hydrogen safety, particularly the safe use of hydrogen in distributed production and consumer environments.*			X		
			Input:					
			DOE Response: DOE has hydrogen safety guidelines currently on its Web site for all researchers to follow. A Hydrogen Safety Review Panel, consisting of outside experts in the field, has been formed. Education and training will be developed for fire marshals and first responders. All these activities will be coordinated with the Department of Transportation.					
8	H	*ES-7*	*DOE should increase emphasis on electrolyzer development with a target of $125/kw, and a significant increase in efficiency towards a goal of 70% (LHV). In parallel, more aggressive electricity cost targets should be set for unsubsidized nuclear and renewable energy that might be used to directly generate electricity. Success in these areas would increase the potential for CO2-free hydrogen production.*				X	X
			Input:					
			DOE Response: DOE fully concurs with this recommendation. We will re-evaluate electrolyzer cost targets.					
9	M	*ES-8*	*DOE should tighten the coupling of its efforts on hydrogen and fuel cell efforts with DOE Fossil Energy programs on carbon capture and storage (sequestration). The Hydrogen Program should participate in all of the early carbon capture and storage projects, which should address the most difficult institutional issues and the challenges relating to public acceptance.*			X		
			Input:					

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			DOE Response: DOE fully concurs on the important linkage among all Departmental hydrogen production activities and carbon sequestration efforts. We will look for ways to better integrate all of the research. DOE hydrogen-based coal research and carbon capture/storage work are under the same manager (Mr. Lowell Miller) in the Office of Fossil Energy.					
10	H	*ES-9 and 9.8*	*DOE should develop its hydrogen RD&D plan to improve integration and balance of activities within the Office of Energy Efficiency and Renewable Energy (EERE); Office of Fossil Energy (FE); Office of Nuclear Energy; Science and Technology (NE), and the Office of Science (SC). The committee believes that production, distribution and dispensing portions are under funded due to earmarks. The committee also believes that the hydrogen program, in an attempt to meet extreme challenges set by senior government officials and DOE leaders, has tried to establish RD&D activities in too many areas, creating a diverse and unfocused program. Therefore, prioritizing the efforts within and across program areas, establishing milestones and go/no-go directions, and adjusting the program on the basis of results are important. The committee also believes that the probability of success is greatly increased by partnering with a broader range of academic and industrial organizations possibly including an international focus, and establishing an independent program review process and board.*	X+		X		
			Input:					
			DOE Response: • DOE is currently developing a program management plan to improve integration across the four offices. • DOE will use the NRC's recommendation concerning research priorities in finalizing the program's Multi-Year RD&D Plan. [DOE requested that the NRC do the study to get input on priorities and strategies.] We have already established hundreds of milestones to measure progress. • Earmarks deter us from using competitive processes through which we can select the people/organizations with the best capability and ideas to perform the research. • The Program is increasing its exploratory research to include a broader range of academic institutions. The industry component has always been strong. • Pending approval of the Energy Bill, the DOE will establish an Advisory Committee which reports directly to the Secretary of Energy and a periodic peer review by the National Research Council.					
11	H	*ES-10 and 9.5*	*The committee believes that there should be a shift in the hydrogen program away from some development areas towards exploratory work (such as with hydrogen storage). Areas that could benefit from exploratory research include delivery systems, pipeline materials, electrolysis, and materials science. The execution of such changes would be facilitated by the establishment of DOE-sponsored academic energy research centers that would focus on interdisciplinary areas of new science and engineering in nanostructures, and modeling for materials design.*			X	X	

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			Input:					
			DOE Response: DOE concurs with this recommendation to put more emphasis on exploratory research. In fact, the President's FY 2005 budget includes $29 million of "new" money for the Office of Science to conduct basic research in hydrogen. We also are currently establishing (competitively) "Centers of Excellence" in hydrogen storage with three National Laboratories and over 20 universities. We will look to expand this model in the areas of hydrogen production/delivery and fuel cell research.					
12	H	*ES-11 and 9.9*	*The committee recommends that these 5 areas receive increased emphasis:* *• Fuel cell vehicle development – increase R&D to facilitate breakthroughs in fuel cell costs and durability of fuel cell materials, as well as breakthroughs in on-board hydrogen storage systems.* *• Distributed hydrogen generation – increase R&D in small scale natural gas reforming, electrolysis, and new concepts for distributed hydrogen production systems.* *• Infrastructure analysis – accelerate and increase efforts in systems modeling and analysis for hydrogen delivery with the objective of developing options and helping guide R&D in large-scale infrastructure development.* *• Carbon Sequestration and FutureGen – accelerate development and early evaluation of the viability of carbon capture and storage on a large scale because of its implications for the long-term use of coal for hydrogen production. Continue FutureGen project as a high priority task.* *• CO2 free energy technologies – increase emphasis on the development of wind energy-to-hydrogen for the transitional and longer term. Increase exploratory and fundamental research on hydrogen production by photobiological, photoelectrochemical, thin-film solar, and nuclear heat processes.*	X+				
			Input:					
			DOE Response: DOE fully concurs with this recommendation and will be changing its planning documents to reflect these priority areas.					
			CHAPTER 3 - THE DEMAND SIDE: HYDROGEN END-USE TECHNOLOGIES					
13	H	*3-1a., similar to ES-2*	*Given that large investments are still needed in fuel cell technology and given that industry is investing in considerable funding in technology development, increased government funding on R&D should be dedicated to the research on breakthroughs in on-board storage systems, fuel cell costs, and in materials for durability in order to attack known inhibitors to the high volume production of fuel cell vehicles.*	X+				
			Input:					
			DOE Response: DOE concurs with this recommendation. Because industry also is investing significantly in technology development, DOE is shifting work away from developing systems and subsystems, and focus on exploratory research with the highest risk technical barriers. We agree that storage and fuel cell costs/durability are two major fundamental research issues.					

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14	H	3.1b.	*Since a hydrogen transportation economy will probably not emerge without the development of reasonably-priced, energy-efficient fuel cells, the transportation portion of the DOE's RD&D program should emphasize fuel cells and their associated storage systems at the expense of "transitional technologies" such as on-board reformers and hydrogen ICE. Since transitional technologies involve "development," funding for these technologies should be provided by industry. Of course, some component breakthrough technologies for reformation might be justified in supply-side programs, and the results might be applicable to on-board reformation.*	X-				
			Input:					
			DOE Response: DOE will have a "go/no go" decision regarding the feasibility of on-board reformers in 6 months. Prior to the President's Initiative we developed this particular pathway because it avoids the barriers associated with hydrogen storage and infrastructure. Now that we have the focus and resources for hydrogen, we can tackle the technical barriers with hydrogen storage and infrastructure. DOE's relative funding levels for hydrogen ICE and fuel cell research is consistent with the higher longer-term advantages of hybrid FCVs and the need to maintain a critical level of research in interim technologies that could contribute to our long-term goal of a hydrogen economy. DOE is investing a relatively small amount (~$1M/yr) on pre-competitive hydrogen ICE research.					
15	H	3-2	*DOE should discontinue PEM applied R&D program for stationary systems. The $7.5 million annual budget (FY03 and FY04 requests) could be applied to PEM fundamental and basic issues (exploratory research) for all applications.*	X-				
			Input:					
			DOE Response: DOE is considering this recommendation. We concur with the shift towards exploratory research for all applications which could significantly impact US energy security and CO2 emissions reductions. (Since NRC states the hydrogen program is under-funded, one approach is to use these resources for fundamental research to solve fuel cell costs/durability issues to benefit both stationary and transportation applications).					
16	M	3-3	*As the DOE develops its strategy for the hydrogen economy with respect to the role of public research, development and demonstration policies, it should sponsor an independent study of lessons learned with respect to lack of success and widespread market acceptance of previous alternative fuel technologies, as well as other technologies developed for transportation and stationary power systems. The purpose would be as follows: 1) assess the role of government policy and its stability as it affects industry and consumer behavior; 2) to affect strategies related to the introduction of hydrogen in the end-use sectors; 3) to avoid repeating mistakes of prior-technology introduction programs, such as those for EVs, NGVs, and PAFCs for distributed generation. In addition, strengths and weaknesses of the PNGV and HEV development should be analyzed as the FreedomCar program is structured for the development of fuel cell vehicles.*			X		
			Input:					

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			DOE Response: DOE is considering this recommendation. We envision a broader study with two phases: 1) a top-level study on success/failure of alternative-fueled vehicle programs and corresponding legislative policies; and 2) a more detailed technology review, and how well these vehicles/fuels met customer requirements and achieved economic viability.					
17	L	3-4	*An independent, in-depth study, similar to the present study on the transportation sector, should be initiated to analyze the opportunities for hydrogen in stationary applications and to make recommendations related to RD&D strategy that incorporates considerations of both transportation and stationary sectors.*			X		
			Input:					
			DOE Response: DOE believes that this recommendation is not that critical in the near term. We do realize that addressing CO2 reduction in the power sector is important; however, tremendous synergies exist between transportation and stationary applications, especially in the areas of intermittent renewables, such as wind and solar. DOE is demonstrating the "power park" concept, where hydrogen is produced for stationary power as well as for refueling vehicles. For larger distributed generation applications, DOE believes that natural gas is the primary fuel of choice in the near term to produce power in high temperature fuel cells, gas turbines and other low-emission, power conversion technologies. Across both technologies, the real driver for hydrogen is in transportation applications. Once a national hydrogen delivery infrastructure is in place then hydrogen can play a bigger role in larger stationary power applications.					
			CHAPTER 4 - TRANSPORTATION, DISTRIBUTION AND STORAGE OF HYDROGEN					
18	H	4-1	*Increased R&D investment in support of breakthrough approaches should be made in small-scale reformer and electrolyzer development with the aim of increasing efficiency and reducing capital costs. A related goal should be to increase the safety and reduce the capital intensity of local hydrogen storage and delivery systems, by incorporating part or all these capabilities in the hydrogen generating technologies.*	X+			X	
			Input:					
			DOE Response: DOE agrees with this recommendation. We believe that a distributed natural gas infrastructure (using reformers) and development of electrolyzer technologies are critical for the transition to the hydrogen economy. The President's FY 2005 request, has requested 3 times more funding than appropriated in FY 2004 in safety-related areas.					

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19	M	4-2	*The DOE should halt efforts on high-pressure tanks and cryogenic liquid storage for use on board the vehicle. These technologies are in a pre-commercial development phase, and in the committee's view they have little promise of long-term practicality for light-duty vehicles. The DOE should apply most if not all of its budgets to the new areas described in Finding 4-1 with the objective of identifying as quickly as possible a relatively few, promising technologies. Where relevant, efficient waste-recycling studies for the chemically bound approaches should be part of these studies. Even during this winnowing process the DOE should continue to elicit new concepts and ideas, because success in overcoming the major stumbling block of on-board storage is critical for the future of transportation use of fuel cells.*	X-		X		
			Input:					
			DOE Response: DOE generally agrees, and plans on winding down its high pressure tank development. In the near future, DOE may continue low-cost carbon materials work to support tanks. We are establishing a robust experimental development program for low-pressure, solid-state hydrogen storage materials. Under this effort, we are creating three "Centers of Excellence" which utilize the best resources available at national labs and universities.					
20	H	4-3	*Systems modeling for the hydrogen supply evolution should be started immediately, with the objective of helping guide research investments and priorities for the transportation, distribution, and storage of molecular hydrogen. In addition, parallel analysis of the many alternatives for other means of supplying hydrogen to fuel-cell powered facilities and vehicles should be performed; such analysis is needed to prevent wasteful expenditures and to help focus attention on viable technology that would potentially compete with the direct supply and delivery of molecular hydrogen and that might be useful for all or portions of the future hydrogen economy.*	X+				
			Input:					
			DOE Response: DOE fully agrees with this recommendation. Based on the interim letter report from the National Research Council (NRC) dated April 4, 2003, DOE is already developing independent systems analysis capability for the hydrogen program at the National Renewable Energy Laboratory (NREL). (There will be a "firewall" between the systems analysis work and other research projects at NREL.) A portion of the increase in the FY 2005 budget (over the FY 2004 appropriation) will be used in creating this capability.					
21	M	4-4	*Research and technology development should be carried out in support of novel concepts that promise major improvements in the cost and efficiency of compressors for molecular hydrogen and reductions in the cost of pipeline materials, valves, and other leak-prone components of its distribution system. Initial research should focus on those components that are directly related to distributed hydrogen production. In later years, research should shift to components of large, centralized production plants with extensive pipeline and storage facilities. The committee believes that current DOE plans call for research that relates primarily to centralized molecular hydrogen manufacture – a need that is many decades in the future – and consequently may shortchange other, more immediate needs.*			X	X	
			Input:					

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			DOE Response: DOE agrees. Due to funding constraints in the past, we have yet to emphasize hydrogen delivery research. In the future, we intend to build up that part of our hydrogen program. In addition, DOE will be working closely with DOT in this critical area.					
			DOE is going to shift emphasis away from central production of natural gas because the technology is rather mature and because of the import implications (in the long-term, if we rely on natural gas as primary source).					
			CHAPTER 7 - CARBON CAPTURE AND STORAGE					
22	M	7-1	*The DOE's hydrogen program needs to be well integrated with the carbon capture and storage program, to assure that any expanded role for hydrogen produced from fossil fuel has a positive impact on the mitigation of climate change. Such integration will enable the hydrogen program to identify critical technologies and research areas that can enable hydrogen production from fossil fuels with CO2 capture and storage.* *Tightening the coupling of the two programs should facilitate setting priorities in those portions of the hydrogen program addressing hydrogen production from fossil fuels and biomass. It should also promote the exploration of overlapping issues – for example, the co-capture and co-storage with carbon dioxide of pollutants such as sulfur during hydrogen production.* *Because of the hydrogen program's large stake in the successful launching of carbon capture and storage activity, the hydrogen program should participate in all of the early carbon capture and storage projects, even those that do not directly involve carbon capture during hydrogen production. These projects will address the most difficult institutional issues and the challenges related to issues of public acceptance, which have the potential of delaying the introduction of hydrogen in the marketplace.*		X	X		
			Input:					
			DOE Response: DOE agrees that these areas should be closely coordinated, and in fact, the manager (Lowell Miller) at the Office of Fossil Energy responsible for coal-based hydrogen research is also responsible for the carbon sequestration activities. DOE will look at better ways to integrate the hydrogen program with the carbon sequestration activities					
23	H	7-2	*The FutureGen project should be managed to encourage the development of technologies that integrate hydrogen production with CO2 capture. FutureGen should have strong research and development components.*			X		
			Input:					
			DOE Response: DOE agrees with this recommendation. Because of the abundance of coal as a domestic energy source, the DOE believes that carbon capture and storage technologies have to be feasible in order for coal to be pursued as a long term option. FutureGen represents an Administration priority, and DOE intends to look at all domestic resources, including coal, as part of its energy security efforts.					
24	H	7-3	*The DOE should foster public discussion of institutional factors affecting carbon capture and storage, including property rights at storage sites, the management of infrastructure, insurance and liability, and the funding of monitoring and verification, including those efforts over the very long term.*		X			

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			The DOE should foster the identification of the issues likely to have the greatest impact on public acceptance of carbon capture and storage. It should encourage public discussion of local environmental and health risks. It should encourage public discussions of what constitutes "adequate" storage, from the standpoint of durability and verifiability. It should explore the merits of broad agreement that early criteria be more permissive and later ones tougher.					
			Input:					
			DOE Response: DOE agrees. We have started fostering public discussion through the regional carbon sequestration partners, which involves academic, industry, state/local, etc.					
			CHAPTER 8 - HYDROGEN PRODUCTION TECHNOLOGIES					
25	H	8-1	*The DOE should focus its natural gas conversion program on the development of a hydrogen generation appliance that can be mass-produced and operated reliably and safely in a typical fueling station with only periodic attention, with the goal of having prototype designs in 5 to 7 years. Two prototype designs, one incorporating partial oxidation (or autothermal reforming) and the other steam methane reforming, should be pursued. Funding should be adjusted to ensure that this goal is achieved. In addition, the DOE should downsize its efforts on centralized generation, pursuing only those developments that would be applicable to distributed.*			X	X	X
			Input:					
			DOE Response: DOE agrees with this recommendation. Natural gas as a feedstock for hydrogen generation makes sense in the near term given the lack of delivery infrastructure for hydrogen. Market penetration during the "transition" period will not be high enough to affect natural gas supplies. However, we are only promoting these technologies for transition applications. This is not a long-term approach – we don't want to substitute oil dependency for natural gas dependency by relying on natural gas too heavily in the long-term.					
26	M	8-2	*The committee recommends that the DOE give appropriate attention in its program to the development of an integrated fueling facility, including the generation appliance and is ancillary subsystems, to minimize cost and to improve efficiency, safety, and reliability.*			X		
			Input:					
			DOE Response: DOE agrees with this recommendation. In fact, DOE is working with industry to develop integrated facilities addressing bulk storage safety, operations control systems, and challenges to equipment manufacturability.					
27	M	8-3	*Coal is a viable option for making hydrogen in large, centralized plants when the demand for hydrogen becomes large enough to support an associated distribution system. Thus, coal should be a significant component of any domestic research and development program aimed at producing large quantities of hydrogen for a possible U.S. hydrogen economy.*			X		
			Input:					
			DOE Response: DOE concurs - again carbon capture and sequestration is essential for coal to be considered a significant component. DOE appreciates the committee's support for the FutureGen project.					

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28	M	8-4	*Because there are a number of similarities between the integrated gasification combined cycle process and the coal-to-hydrogen process, the committee endorses the continuation of both programs in tandem at budget levels that are determined to be adequate to meet the programs goals.*			X		
			Input:					
			DOE Response: DOE concurs with this recommendation.					
29	H	8-5	*The committee commends the DOE on its initiative in undertaking the FutureGen Project and recommends that the DOE move ahead with the project because of its promise of demonstrating coal-to-hydrogen production coupled with sequestration at a significant scale and its use as a large-scale test bed for related process improvements. As costs can be very high for this type of demonstration, the overall project size and complexity should be closely monitored by the DOE.*			X		
			Input:					
			DOE Response: DOE concurs with this recommendation and the criteria for the monitoring of this project are currently evolving in parallel with the creation of FutureGen.					
30	H	8-6	*The DOE's nuclear hydrogen program should focus on the options to accomplish water splitting without any CO2 emissions. At this early stage of laboratory scale investigations, the program should involve several options for promising cycles covering catalysts to enhance the reactions at lower temperatures and materials-compatibility issues. Development of the high-temperature steam electrolysis process should be pursued in balance with the thermochemical cycles. The issues of materials durability, reduction of overvoltages, operating pressure effects, and the separation of gas products in an efficient and safe manner should be investigated. If research is successful, one or two processes should be selected for demonstration of the integrated process in a few years.*			X		X
			Input:					
			DOE Response: DOE fully concurs with this recommendation. Because nuclear energy is a carbon free source, it can play a major role in the future hydrogen/electricity mix for the nation.					
31	H	8-7	*A portfolio of research that advances the near-term technologies while examining the innovative approaches needs to be maintained. The total budget covering the thermochemical, electrochemical, and other alternatives should be increased for a few years in order to allow for selecting the most promising approaches for demonstrations. The DOE should promote industry involvement in assessing the economic potential of the various options.*	X+	X	X		
			Input:					
			DOE Response: DOE fully concurs with this recommendation. It is important to look at the viability of several innovative options for the future. A number of different companies are involved in several ongoing DOE topic-specific discussion groups. In evaluating these options, work with industry will concentrate on economic viability.					
32	M	8-8	*The R&D program should involve safety elements of the nuclear-chemical integrated system and aim to establish guidelines to arrest accident propagation from one part of the system to the other*			X	X	

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			Input:					
			DOE Response: DOE fully concurs with this recommendation. Safety is paramount to the commercialization and public acceptance of hydrogen as a transportation fuel.					
33	H	*8-9*	*The DOE's electrolysis technology program should continue to target cost reduction, enhanced system efficiency, and improved durability for distributed-scale hydrogen production from electricity and water. These technology objectives can be advanced through research into (1) lower-cost membranes, catalysts and other cell and system components; (2) membranes and systems that can operate at higher temperatures and pressures; and (3) improved system design and integration with an eye toward low-cost manufacturing. Specifically, the DOE should increase emphasis on electrolyzer development with a target of $125 per kilowatt and a significant increase in efficiency toward a goal of over 70 percent (lower heating value basis).*			X	X	X
			Input:					
			DOE Response: DOE will look at synergies in lowering the cost of fuel cells and how it might also apply to lower costs of electrolyzers. (Electrolyzer is a fuel cell that runs backwards.)					
34	H	*8-10*	*The DOE should emphasize component development and systems integration to enable electrolyzers to operate from inherently intermittent and variable-quality power derived from wind and solar sources*			X		X
			Input:					
			DOE Response: DOE fully agrees, in fact, this project has been initiated to better integrate the wind turbine power control systems with electrolyzer systems.					
35	H	*8-11*	*Wind energy for hydrogen production does not appear at present in the DOE's Multi-Year RD&D Plan. Wind-energy-to-hydrogen systems need to be an important element in DOE's hydrogen program and need to be integrated into the hydrogen production strategy. The Plan should address the technical issues related to costs and capacity factor, particularly wind sites in Class 3 and below*		X	X		
			Input:					
			DOE Response: In the RD&D Plan, the academy reviewed only electrolysis technologies that could use electricity generated from wind, solar, or other renewables. RD&D on wind turbines to generate electricity falls under the EERE's Wind and Hydropower Technologies program. In FY 2004, the Hydrogen Program and the Wind Program cost-shared an analysis to evaluate the opportunities and technology issues for wind-electrolysis in the U.S. Based on the recommendation, we will include plans to increase integration of the wind turbine with the hydrogen generation equipment.					

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36	H	8-12	*The DOE's Multi-Year RD&D Plan should address how to best partner with industry to create robust, efficient and cost-effective wind-electrolysis-hydrogen systems that will be ready for deployment as the distributed hydrogen infrastructure begins to develop. This is particularly important as there needs to be a research and development emphasis on optimizing wind-electrolysis-hydrogen systems. The role that co-production of hydrogen and electricity from wind can play needs to be further analyzed and integrated into future hydrogen production strategies so that potential synergies can be better understood and utilized.*		X	X		
			Input:					
			DOE Response: DOE fully concurs. Based on this recommendation we will change our plan to cover the integration efforts of wind. We plan to increase development activities with industries involved in this technology, and emphasize the benefits of a distributed hydrogen infrastructure. We recognize wind technologies can be distributed and is part of our hydrogen transition strategy. We have, in fact, had a workshop on this topic and plan to conduct additional activities in this area. In the next few months, we plan on conducting a workshop with the European Commission on wind-based hydrogen.					
37	H	8-13	*The committee recommends that DOE deemphasize the current biomass gasification program and refocus its bio-based program on more fundamental research on photosynthetic microbial systems to produce hydrogen from water at high rate and efficiency. DOE should encourage innovative approaches and should make use of important breakthroughs in molecular, genomic and bioengineering research. R&D for co-firing of biomass, for example, with coal, coupled to subsequent carbon sequestration should continue. The DOE should resist pressure for premature demonstration projects of developing technologies.*			X	X	X
			Input:					
			DOE Response: The DOE's Biomass Program offers energy security from foreign oil imports given this is a domestic and sustainable resource. The Biomass Program focuses on thermochemical platforms (production of syngas and bio-oils) as intermediaries for the production of fuel, chemicals and materials. Hydrogen is one output considered from these platforms. DOE agrees with this recommendation and will shift biomass technology emphasis in the Hydrogen Program to exploratory research areas such as photobiological. In our coal gasification work, we will look for synergies that can be applied to biomass gasification for hydrogen production.					
38	H	8-14	*Because of the large volume of hydrogen potentially available from solar energy and its carbon dioxide-free hydrogen, multiple paths of development should be pursued until a clear winning technology emerges for hydrogen production. There is a need for more basic research to provide a low-cost option. More specifically, alternated new technologies for harnessing solar energy should be developed as well as new and novel methods to substantially reduce the manufacturing cost of some of the promising known technologies.*			X	X	
			Input:					

Item	Priority	Rec. Number	Recommendation & Response	Issue Type: Funding	Policy	Prog Mgmt	Tech Team Charter	Technical
			DOE Response: The Solar Program within DOE's EERE Office will continue to work aggressively to lower the costs of thin-film and photovoltaics to make electricity affordable. In addition, the DOE Hydrogen Program and the Solar Program will assess the potential of concentrating solar power for hydrogen production. The Hydrogen Program will focus on exploratory research that will have a large impact on long-term technologies such as photochemical and photobiological to directly produce hydrogen from sunlight. Multiple pathways for direct conversion solar to hydrogen will be pursued.					
39	M	*8-15*	*While basic research in photoelectrochemical as well as other methods that directly convert solar energy to hydrogen should be actively pursued, the route of solar electricity generation coupled with use of an electrolyzer for hydrogen production should also be pursued in a balanced DOE solar program. A more aggressive target for photovoltaic solar of about $0.02 per kilowatt hour (roughly $200 to $300 per kilowatt for the solar module) requires research on new and novel approaches. This will be especially important if improvements in battery storage density and cost are not achieved and hydrogen usage becomes dominant.*			X	X	X
			Input:					
			DOE Response: DOE concurs and will rely on its EERE Solar Program to lower the cost of electricity through photovoltaics. The Solar Program is pursuing several technology pathways to achieve $0.06/kWh by 2020 and even lower costs in the longer term.					
			CHAPTER 9 - CROSSCUTTING ISSUES					
40		*9-1*	*See ES-1*	/	/	/	/	/
41	M	*9-2*	*The DOE should identify potentially useful management tools and capabilities developed elsewhere in the government for managing complex programs and should evaluate their potential for use in the hydrogen program. While such techniques are known to exist, it may well be that they will need to be modified to account for the overriding importance of economics in energy system development*			X		
			Input:					
			DOE Response: DOE concurs with this recommendation and will look at complex development programs carried out by NASA, DOD and others. Within the National Renewable Energy Lab (NREL), Admiral Richard Truly, who headed up NASA, brings management capability to DOE through expert knowledge of systems integration for complex programs. Dale Gardner, who reports to Admiral Truly, leads the systems integration and analysis work and has many years experience running complex programs.					
42	H	*9-3*	*An independent systems analysis group should be established by the DOE to identify the impacts of various hydrogen technology pathways, to assess associated cost elements and drivers, to identify key cost and technological gaps, to evaluate the significance of actual research results, and to assist in the prioritization of research and development directions.*			X		
			Input:					

Item	Priority	Rec. Number	Recommendation & Response	Issue Type: Funding	Policy	Prog Mgmt	Tech Team Charter	Technical
			DOE Response: DOE agrees with this recommendation, and has taken steps to proactively develop systems analysis capabilities based on the NRC's interim report. We have hired new personnel experienced in this area to develop and manage the systems analysis work, and a portion of increase in the FY2005 budget will be used to fund this area.					
43		9-4	*See ES-6*					
44		9-5	*See ES-10*					
45	M	9-6	*The committee commends the DOE for significantly increasing its efforts to bring the energy industry into the hydrogen program. Particularly noteworthy are FreedomCar and the Hydrogen Fuel Initiative and the broad input solicited for the 2002 National Energy Hydrogen Roadmap and the 2003 Hydrogen Posture Plan: An Integrated Research, Development, and Demonstration Plan. The committee encourages the DOE to continue to seek broad input from the energy industry – which includes not only broad, multinational energy companies, but utilities and small companies. In particular, the committee believes that research and development partnerships that would enhance the energy industry and the objectives of the hydrogen program should be encouraged at the level of pre-competitive technology.*		X			
			Input:					
			DOE Response: DOE concurs. We maintain contacts with utilities as well as other agencies and organizations such as Electric Power Research Institute (EPRI), Gas Technologies Institute (GTI), and corporations to collaborate on RD&D with hydrogen technologies. Under the expanded FreedomCAR & Fuel Partnership, we have established technical teams, which include representation from the energy and automobile industries to address detailed approaches for overcoming barriers to the hydrogen economy. (We have established four new technical teams: hydrogen production, hydrogen delivery, systems analysis, and codes and standards).					
46	H	9-7	*The committee recommends that the DOE initiate a comprehensive assessment of the suite of environmental issues anticipated to arise secondary to deployment of a hydrogen energy system, and that the DOE develop a quantitative understanding of the trade-offs and impacts.*		X	X		
			Input:					
			DOE Response: We concur with this recommendation. DOE will look at full environmental analyses to address tradeoffs and impacts to hydrogen systems. This analysis may help uncover issues we have not yet thoroughly addressed.					
47		9-8	*See ES-9*					
48		9-9	*See ES--11*					

Q5. In your testimony, your response to the American Physical Society's (APS's) recommendation against funding large-scale demonstrations was that your demonstrations were "learning demonstrations." What are the specific characteristics that distinguish a learning demonstration? How does it compare in terms of expense to a commercial-scale demonstration? Does this classification-learning demonstration-only apply to the EERE hydrogen demonstrations? How does DOE respond to the APS recommendation against funding large demonstration projects in the context of other programs?

A5. The Department's vehicle and infrastructure learning demonstrations are an extension of our research and critical to meeting the goals of the President's Hydrogen Fuel Initiative, including the program's technical targets that support the 2015 industry commercialization decision. As pointed out during the discussion at the Science hearing by Michael Ramage, Chair of the National Research Council's Hydrogen Committee, "a continuum of basic science, applied research, development, and learning demonstrations is necessary for the successful transition to a hydrogen economy."

The key characteristics of the hydrogen learning demonstrations are:

- Generation of important data that will be used to guide and refocus future research and development efforts
- Identification of operating issues not previously considered, e.g., technology performance in different climates
- Examination of system integration issues
- Evaluation of performance and durability under real-world operating conditions
- Teaming of auto companies and energy companies, which is critical to the success of the initiative
- Leveraging by industry of 50 percent of the funding

Learning demonstrations are not unique to the EERE hydrogen program. Any demonstration that has the characteristics described above would be classified as a learning demonstration. However, the approach of bringing together the automotive and energy industries, which are crucial to the development of a hydrogen infrastructure, is unique. This approach will allow the Department and the Congress to track the progress made and the future potential of this important technology. If the Department does not follow through with the hydrogen learning demonstrations, these essential partnerships will probably dissolve and we will lose valuable financial and technical leverage from industry.

The characteristics of commercial-scale demonstrations are quite different. They involve mature technologies that are ready for market. Commercial demonstrations put the technologies in the hands of the public or fleet operators to encourage or incentivize consumer acceptance and to stimulate market development and expansion. Commercial demonstrations can also be used to subsidize production so that the necessary volumes can be achieved to lower cost. Without a specific program in mind and understanding of relevant policies approved by Congress, the cost of commercial demonstrations cannot be estimated.

We believe that the American Physical Society's overemphasis on basic research is too limiting. Conducting stand-alone basic research is insufficient to achieve our 2015 goals; applied research and technology demonstrations are critical to meeting the technology milestones leading to the 2015 industry commercialization decision and to begin the transition to a hydrogen economy. Basic research is critical to understanding the underlying science that will lead to hydrogen and fuel cell technology improvements in the near-term and potentially "breakthroughs" in the long-term.

Almost 85 percent of the hydrogen budget is for research and development efforts. The Department's mix of hydrogen funding according to OMB circular A-11 for the FY 2005 budget request is as follows:

Basic Research: 12.9 percent

Applied Research: 42.5 percent

Development: 29.2 percent

- Demonstration: 13.4 percent
- Deployment: 2.0 percent (Education)

Q6. What projects related to hydrogen might have been funded if additional funds were available?

A6. Additional funding would be used to address two major challenges facing the hydrogen economy—hydrogen storage capacity and hydrogen production cost. The most critical challenge facing the hydrogen economy is the development of a viable on-board hydrogen storage technology. No technology available today meets consumer requirements in terms of vehicle driving range, weight, volume, and cost. To address this challenge, an elite group of university scientists recommended the establishment of Hydrogen Storage Centers of Excellence to be led by DOE National Laboratories and to include university and industry partners.

Funding for the Centers was requested in the FY 2004 budget. However, due to Congressionally-directed projects in the FY 2004 hydrogen appropriation, no funds were available to start the competitively-selected Centers of Excellence and other university projects. In addition, funds requested in FY 2004 to start critical renewable hydrogen production and delivery R&D projects were not available due to the earmarks. The Department plans to start these storage and production projects with FY 2005 funds, subject to Congressional appropriation.

Q7. In the Vehicle Technologies budget, the largest decrease is due to a completion of the light truck engine program. Given the increase in the size of the U.S. light truck fleet, this type of work would seem extremely relevant to reducing our foreign oil use. What programs or projects were selected as having greater benefits? How has technology improved over the course of the program? Are manufacturers incorporating the improved technology into their vehicles?

A7. The Light Truck Engine (LTE) program was initiated in 1997 to address the increasing fuel consumption in this growing vehicle segment. The primary focus was the development of advanced clean diesel engines that could increase the fuel economy of light trucks and SUVs by 50 percent over a comparable gasoline powered vehicle. Two state-of-the-art diesel engines have been developed that have demonstrated the fuel economy goal and additional technologies have been developed to reduce emissions to Tier 2 levels in short-term testing. These significant advances have paved the way for introduction of advanced clean diesel engines into the light truck market.

There are no other projects that will have a greater near-term impact on reducing oil consumption than the successful implementation of this technology in the light truck market. However, it is felt that federal R&D funding is no longer needed for these engines as final product development will be carried out by industry. One major LTE industry partner is reported to be negotiating the potential production and use of their advanced clean diesel engines with a major vehicle manufacturer (see *Ward's Auto World,* February 1, 2004). The focus of our efforts is shifting to longer-term higher risk research on advanced combustion regimes that have the potential for even higher efficiencies and lower emissions.

Appendix 2:

Additional Material for the Record

HYDROGEN POSTURE PLAN

AN INTEGRATED RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN

February 2004

United States Department of Energy

A National Commitment

In his State of the Union address, President Bush announced a $1.2 billion hydrogen initiative to reverse America's growing dependence on foreign oil and reduce greenhouse gas emissions. The President urged the development of commercially viable hydrogen fuels and technologies for cars, trucks, homes, and businesses.

> *With a new national commitment, our scientists and engineers will overcome obstacles...so that the first car driven by a child born today could be powered by hydrogen, and pollution-free. Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy.*

— President Bush,
State of the Union Address,
January 28, 2003

In submitting his budget request for fiscal year 2004, Energy Secretary Spencer Abraham responded to the President's call by outlining a key role for the U.S. Department of Energy in coordinating this multi-faceted technology development effort:

> *Government coordination of this huge undertaking will help resolve one of the difficulties associated with the development of a commercially viable hydrogen fuel-cell vehicle:...Which comes first, the vehicle or the infrastructure of manufacturing plants, distribution and storage networks, and the convenient service stations needed to support it?...[The Department will work with all stakeholders] to develop both the vehicle and the infrastructure in parallel—and by so doing, advance a commercialization decision by 15 years, from 2030 to 2015.*

— Energy Secretary Abraham,
2004 DOE Budget Submission
February 3, 2003

The National Academies' report on the DOE hydrogen program concludes that:

> *A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy resources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants.*

— The National Academies
Committee on Alternatives and Strategies for
Future Hydrogen Production and Use
February 2004

This document describes the Department's plan for successfully integrating and implementing technology research, development, and demonstration activities needed to cost-effectively produce, store, and distribute hydrogen for use in fuel cell vehicles and electricity generation.

DOE's Integrated Plan for Action

Energy is the life-blood of our Nation. It is the mainstay of our standard of living, economy, and national security.

In the United States demand for oil is projected to increase by nearly 50 percent by 2025. Petroleum imports already supply more than 55 percent of U.S. domestic needs, and those imports are projected to increase to more than 68 percent by 2025. Our growing dependence on foreign sources of energy threatens our national security. As a Nation, we must work to reduce our dependence on foreign sources of energy in a manner that is affordable and preserves environmental quality.

Vision for the Hydrogen Economy

Hydrogen is America's clean energy choice.

Hydrogen is flexible, affordable, safe, domestically produced, used in all sectors of the economy, and in all regions of the country.

A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond, February 2002.

Clean forms of energy are needed to support sustainable global economic growth while mitigating impacts on air quality and the potential effects of greenhouse gas emissions. To address these challenges, the President's *National Energy Policy* and the U.S. Department of Energy's (DOE's) Strategic Plan call for expanding the development of diverse domestic energy supplies. The President has proposed $1.2 billion over the next five years to support a new Hydrogen Fuel Initiative. The Initiative will accelerate the pace of research and development on the hydrogen production and distribution infrastructure needed to support hydrogen-powered fuel cells for use in transportation. It will also address the need for appropriate safety codes and equipment standards and for improved public education on hydrogen as an energy carrier.

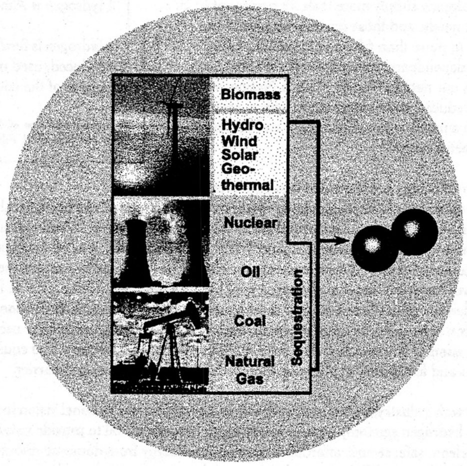
Working with industry, the Department developed a long-term national vision for moving toward a hydrogen economy—a solution that holds the potential to provide virtually limitless clean, safe, secure, affordable, and reliable energy from domestic resources. To realize this vision, the Nation must develop and demonstrate advanced hydrogen fuel cell and infrastructure technologies while continuing to promote complementary near-term energy efficiency and renewable energy solutions. Toward this end, the Department has worked with public and private organizations from across the country to develop a *National Hydrogen Energy Technology Roadmap*. The Roadmap identifies the technological research, development, and demonstration steps required to make a successful transition to a hydrogen economy. The Roadmap stresses the need for parallel development of model building codes and equipment standards to enable technology integration into commercial energy systems, and outreach programs to effectively educate local government officials and the public, who will determine the long-term acceptance of these technologies.

DOE Promotes Hybrid Vehicles as its Near-term Strategy

Hydrogen has the long-term potential to reduce our dependence on foreign oil and lower our carbon and criteria emissions from the transportation sector. In the next two decades, conservation and increased efficiency through the use of gasoline-electric hybrid vehicles are the best options for reducing oil use and emissions. DOE provides over $90 million annually for development of hybrid vehicle components for light-duty applications. In addition, the Federal government offers a $1,500 tax deduction for qualifying hybrid vehicles purchased in 2004. Also, many states are taking actions (such as waiving sales tax) to promote hybrid vehicles.

This *Hydrogen Posture Plan* describes how DOE will integrate its ongoing and future hydrogen R&D activities into a focused Hydrogen Program. The program will integrate technology for hydrogen production (from fossil, nuclear, and renewable resources); infrastructure development (including delivery and storage); and fuel cells for stationary and transportation applications. A coordinated DOE Hydrogen Program will improve the effectiveness and accountability of DOE's research, development, and demonstration (RD&D) activities and strengthen its contribution to achieving the technical milestones on the road to a hydrogen economy.

DOMESTIC HYDROGEN PRODUCTION OPTIONS



...the first car driven by a child born today could be powered by hydrogen, and pollution-free.

— President Bush,
State of the Union Address,
January 28, 2003

Executive Summary

The *Hydrogen Posture Plan* was prepared by the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) in response to a directive by Energy Secretary Spencer Abraham. As directed, EERE developed the Plan with the support of the DOE Offices of Fossil Energy, Science, and Nuclear Energy, Science and Technology to outline the activities, milestones, and deliverables that the Department plans to pursue to support America's shift to a hydrogen-based energy system. The *Hydrogen Posture Plan* integrates the Department's planning and budgeting for program activities that will help turn the concept of a hydrogen-based economy into reality. More specifically, this Plan outlines the Department's role in hydrogen energy research and development in accordance with the *National Hydrogen Energy Roadmap* released by Secretary Abraham on November 12, 2002, and lays the foundation for a coordinated response to the President's goal for accelerated research on critical path hydrogen fuel cell and infrastructure technologies.

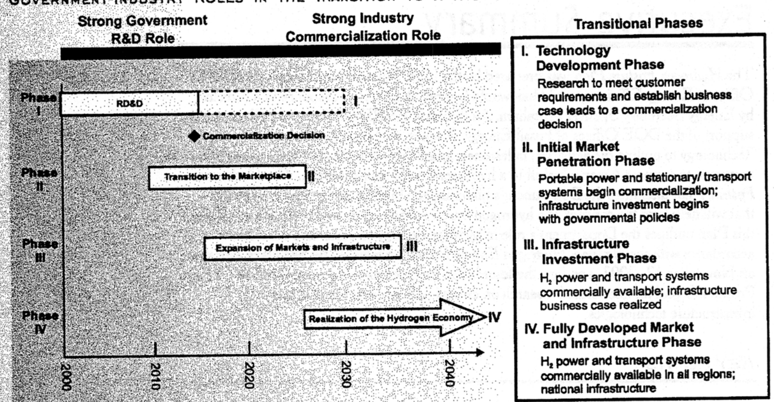
Key Points

- Use of hydrogen as an energy carrier can enhance long-term energy security while mitigating the effects of air pollution and greenhouse gas emissions. The *National Hydrogen Vision*, developed in response to the President's *National Energy Policy*, envisions hydrogen as a flexible, safe, affordable, domestic energy resource used in all sectors of the economy and all regions of the country. Hydrogen will become America's "clean energy choice," joining electricity as a primary energy carrier and providing the foundation for a globally sustainable energy system.
- Technical challenges to achieving a hydrogen economy include lowering the cost of hydrogen production, delivery, storage, conversion, and end-use applications. Additional needs include effective building codes and equipment standards to address safety issues as well as outreach and education campaigns to raise awareness, accelerate technology transfer, and increase public understanding of hydrogen energy systems. These challenges and the general paths forward are discussed in detail in the *National Hydrogen Energy Roadmap*.

> *"This committee believes that investigating and conducting RD&D activities to determine whether a hydrogen economy might be realized are important to the nation."*
>
> — The National Academies Committee on Alternatives and Strategies for Future Hydrogen Production and Use February 2004

- The *Hydrogen Posture Plan* integrates existing and future activities by DOE to pursue the R&D priorities laid out in the Roadmap and overcome the related technical challenges. DOE and other agencies of the Federal government will have to play a leadership role in the transition to a hydrogen economy. DOE envisions a four-phase process to fully realize a hydrogen economy by 2030-2040, as shown in the figure on the following page.
- Because the research is not guaranteed to be successful and better options could arise for addressing foreign oil dependency and carbon emissions in the transportation sector, a commercialization decision precedes the infrastructure investment phase.
- The Federal government will play a key role in the near term, while technologies are being developed and demonstrated in limited markets. If the research is successful in

GOVERNMENT-INDUSTRY ROLES IN THE TRANSITION TO A HYDROGEN ECONOMY



The timeframe is long and the investment is large to develop a hydrogen and transportation market that reduces our Nation's dependence on foreign sources of energy while minimizing environmental impacts.

the mid term, the Federal government will become an early technology adopter, enacting policies that will nurture the development of an industry capable of delivering significant quantities of hydrogen to the market place. Industry's role will become increasingly dominant in the mid- to late- stages.

✦ The Department's mission is to assist in developing and demonstrating technologies for producing, storing, and delivering hydrogen in an efficient, clean, safe, reliable, and affordable manner. Some of these activities directly contribute to the development of a hydrogen economy, such as those aimed at hydrogen production, storage, and development of direct hydrogen fuel cells for transportation applications. Related DOE efforts that also contribute to achieving a hydrogen economy include the development of high-temperature fuel cells for stationary applications and carbon sequestration technologies.

✦ Key program milestones for achieving a hydrogen economy include the following:
- On-board hydrogen storage systems with a 9% capacity by weight to enable a 300 mile driving range.
- Hydrogen production from natural gas or liquid fuels at a price equivalent to $1.50 per gallon of gasoline at the pump, untaxed, no carbon sequestration, at 5,000 psi.
- Polymer electrolyte-membrane automotive fuel cells that cost $30-45 per kilowatt and deliver 5,000 hours of service (service life of vehicle).
- Zero emission coal plants that produce hydrogen and power with carbon capture and sequestration at $0.80 per gallon of gasoline equivalent (gge) at the plant gate ($1.80/gge delivered).
- Hydrogen production from wind-based electrolysis approaching $2.00 per gallon of gasoline equivalent untaxed (using wind electricity at $0.04 per kwh), delivered at 5,000 psi.
- Hydrogen fuel delivery technologies that cost $1.00 per gallon of gasoline equivalent.

NEXT STEPS

- ✦ Coordinate the detailed multi-year RD&D plans and priorities for hydrogen and related technology development efforts in the Department to make them consistent with this planning document and the National Academies' study requested by DOE.

- ✦ To strengthen coordination within DOE, establish a working group composed of representatives from the Offices of Energy Efficiency and Renewable Energy; Fossil Energy; Nuclear Energy, Science and Technology; Science; Management, Budget, Evaluation/CFO; and Policy and International Affairs (in an oversight capacity). This working group should meet periodically to perform the following functions:
  - Evaluate the Department's progress in meeting milestones and performance goals in hydrogen and related activities.
  - Strengthen information exchange on technical developments.
  - Help ensure continued close integration among the Department's hydrogen-related activities (e.g., budgeting, execution, evaluation, and reporting).
  - Provide suggestions for improving management and technical performance.
  - Collaborate on systems analysis to understand the economic, energy, and environmental impacts of alternative technology pathways.

- ✦ Prepare a Program Management and Operations Plan to provide further detail on the overall management and integration of the Department's Hydrogen Program, including reporting requirements, oversight/advisory roles and responsibilities, and baseline requirements, cost, and schedule.

- ✦ Reflect the importance of the following activities in the Department's out-year planning and budgeting:
  - Exploratory research in hydrogen storage, production, and fuel cell cost and durability.
  - Hydrogen delivery and development of infrastructure (these activities need to be closely coordinated with the Department of Transportation (DOT), which is responsible for efforts to ensure the safety of the hydrogen delivery system).
  - Economic and systems analyses for determining and mitigating investment risks associated with hydrogen infrastructure and related technologies (e.g., fuel cell systems engineering and manufacturing plants).

- ✦ Increase the energy industry participation in the initiative, in recognition of the industry's key role in energy production and delivery infrastructures. Greater energy and utility industry participation is vital to a successful transition to a hydrogen economy.

- ✦ Strengthen and continue existing interagency coordination efforts to ensure that Federal investments in hydrogen energy development are leveraged to the maximum extent. The following agencies are participating with the Department of Energy in the Hydrogen Interagency Research and Development Task Force to discuss national hydrogen and related activities: Departments of Defense, Commerce, Transportation, Agriculture, and State; Office of Management and Budget; Office of Science and Technology Policy; National Science Foundation; National Institutes of Standards and Technology; Environmental Protection Agency; and National Aeronautics and Space Administration.

- ✦ Strengthen international cooperation on hydrogen-related research, development, and demonstration programs and on the development of interoperable codes and standards through the International Partnership for the Hydrogen Economy.
- ✦ Be aware of the nation's regulatory framework of energy, economic, and environmental policies at the federal, state, and local levels, and work with the appropriate agencies to coordinate the timing of policy instruments and regulatory actions to allow technology to meet market requirements.

Table of Contents

1. Introduction

Today, America is confronted by major energy challenges:

- Attaining greater energy and economic security by reducing dependence on foreign energy supplies,
- Increasing affordable domestic energy supplies to meet anticipated demand, and
- Reducing air pollution and addressing concerns about climate change.

The Administration's *National Energy Policy (NEP)* and the U.S. Department of Energy's (DOE's) Strategic Plan both call for reducing U.S. reliance on imported oil. The NEP also acknowledges the need to increase energy supplies and use more energy-efficient technologies and practices. As highlighted in the NEP, energy-related activities are the primary source of air pollution and greenhouse gas emissions. The need for clean, abundant, affordable, domestically produced energy has never been greater.

As President Bush acknowledged in his January, 2003, State of the Union address, hydrogen has the potential to play a major role in America's future energy system. DOE recognizes that the development of this abundant element as an "energy carrier" will help address national concerns about energy supply, security, and environmental protection.

Hydrogen can be derived from a variety of domestically available energy sources (see several example pathways in Appendix A). It has a wide variety of applications, including fuel for automobiles and distributed and central electricity and thermal energy generation.

The Department also recognizes that the attainment of a "hydrogen economy" will require a coordinated national effort and sustained activities by diverse public and private stakeholders. Today hydrogen is commonly used in industrial applications to manufacture petrochemicals and fertilizers. The existing hydrogen production and distribution infrastructure is insufficient, however, to support widespread use of hydrogen for energy. With the exception of aerospace and rocket propulsion applications, the current hydrogen industry does not produce hydrogen as an energy carrier or as a fuel for energy generation, except for pilot-scale R&D projects. Taking this step will require research, development, and demonstrations to improve performance and lower costs for hydrogen production, delivery, storage, conversion, and end-use applications, and activities to provide education and experience to safety and code officials. The President's proposed $1.2 billion Hydrogen Fuel Initiative will accelerate R&D funding in each of these areas.

Positive Attributes of Hydrogen as an Energy Carrier

Addresses national energy security, air quality, and greenhouse gas emissions:

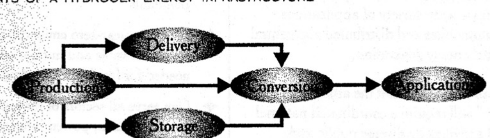
- Can be derived from diverse domestic resources (fossil, nuclear, renewable)
- Compatible with high-efficiency fuel cells, combustion turbines and reciprocating engines to produce power with near-zero emissions of criteria pollutants
- Produces near-zero emissions of greenhouse gases from renewable and nuclear sources (sequestration needed for fossil-based hydrogen)
- Can serve all sectors of the economy (transportation, power, industrial, and buildings)

As a first step, the Department oversaw a National Hydrogen Vision and Roadmap process and incorporated the opinions and viewpoints of a broad cross-section of stakeholders in two key documents: *A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*, and the *National Hydrogen Energy Roadmap*.[1]

> **"Critical Path" Technologies Necessary for Developing a Hydrogen Economy**
>
> - Lower cost of producing and delivering hydrogen
> - More compact, light weight, lower cost, safe and efficient storage systems
> - Lower cost materials for advanced conversion technologies, especially fuel cells
> - More effective and lower cost carbon-capture and sequestration processes
> - Designs and materials that maximize the safety of hydrogen use

This document, the U.S. Department of Energy's *Hydrogen Posture Plan*, has been prepared to outline the activities, milestones, and deliverables that the Department must pursue to promote America's shift to a hydrogen-based energy system, the key elements of which are shown in Figure 1, below. Among the topics addressed are the schedules for evaluating and developing technologies to: a) produce and deliver hydrogen using various domestic resources (e.g., natural gas and coal using capture and sequestration of carbon dioxide; renewables including wind, solar, and biomass; and nuclear energy); b) store hydrogen; c) convert hydrogen to useful energy through advanced fuel cells and other devices; d) conduct limited "learning" demonstrations to measure technology progress; e) address education needs; and; f) develop and verify appropriate codes and standards for a variety of applications. The Posture Plan also addresses the critical role of developing a viable hydrogen infrastructure in achieving a successful FreedomCAR Partnership, a government-industry initiative for the advancement of high-efficiency hydrogen-powered fuel cell vehicles; and the important role of government policies in overcoming economic and institutional barriers to the development of a hydrogen infrastructure.

FIGURE 1. ELEMENTS OF A HYDROGEN ENERGY INFRASTRUCTURE



Production
- The production of hydrogen from fossil fuels, biomass, or water
- Involves thermal, electrolytic, and photolytic processes

Delivery
- The distribution of hydrogen from production and storage sites
- Involves pipelines, trucks, rail and barges
- Involves efficient reversible solid or liquid carrier systems

Storage
- The confinement of hydrogen for delivery, conversion, and use
- Involves tanks for both gases and liquids at ambient and high pressures
- Involves reversible and irreversible solid- and liquid-state systems, including metal and chemical hydrides

Conversion
- The making of electricity and/or thermal energy
- Involves combustion turbines, reciprocating engines, and fuel cells

End-Use Energy Applications
- The use of hydrogen for transportation systems such as fuel-cell vehicles, internal combustion engines, and for portable power devices
- The use of hydrogen for stationary energy generation systems, including distributed energy systems, central generating stations, and combined heat and power applications
- Involves performance and safety evaluations and development of codes/standards

[1] These documents can be found on the internet at www.eere.energy.gov/hydrogenandfuelcells

2. Key Drivers for a Hydrogen-Based Energy System

Three major factors compel us to consider new approaches to the way the United States produces, delivers, and uses energy. These drivers are

- Energy security
- Environmental quality, and
- International competitiveness

Energy Security

The United States must expand its domestic supply of energy. America's transportation sector relies almost exclusively on refined petroleum products. As shown in Figure 2, close to one-half of the petroleum consumed for transportation in the United States is imported, and that percentage is expected to rise steadily for the foreseeable future. On a global scale, petroleum supplies will be in increasingly higher demand as highly populated developing countries expand their economies and become more energy intensive. Hydrogen-powered fuel cell vehicles would not be dependent on foreign oil, since the hydrogen can be produced almost entirely from diverse domestic sources of fossil fuel, renewable, and nuclear energy. Its use as a major energy carrier would also provide the United States with a more efficient and diversified energy infrastructure, with a variety of options for fueling central and distributed electric power generation systems.

Fuel Cells Offer Large Improvements in Energy Efficiency and Emissions

Fuel cells represent a radically different approach to energy conversion, one that could replace conventional power generation technologies like engines and turbines in applications such as automobiles and small power plants. Fuel cells, like batteries, directly convert chemical energy into electric power, without the intermediate production of mechanical work. But unlike batteries, fuel cells do not need recharging; instead they use fuel to produce power as long as the fuel is supplied. Fuel cells operate quietly and are relatively compact. Largely because of these characteristics, hydrogen-powered fuel cells promise:

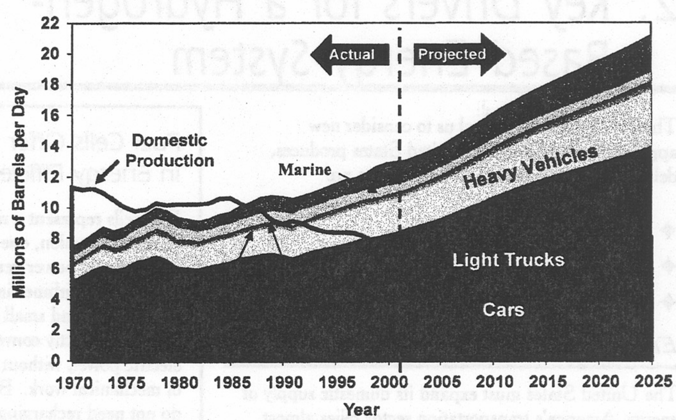
- For vehicles, over 50% reduction in fuel consumption compared to a conventional vehicle with a gasoline internal combustion engine
- Increased reliability of the electric power transmission grid by reducing system loads and bottlenecks
- Increased co-generation of energy in combined heat and power applications for buildings
- Zero- to near-zero levels of harmful emissions from vehicles and power plants

Environmental Quality

Air quality is a major national concern. It has been estimated that 60% of Americans live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment. As shown in Figure 3, personal vehicles and electric power plants are significant contributors to the nation's air quality problems. Most states are now developing strategies for reaching national ambient air quality goals and bringing their major metropolitan areas into attainment with the requirements of the Clean Air Act. The introduction of hydrogen-based commercial bus fleets is one of the approaches that states are considering to improve air quality.

The combustion of fossil fuels accounts for the majority of anthropogenic greenhouse gas emissions (chiefly carbon dioxide, CO_2) released into the atmosphere. The largest sources of CO_2 emissions are the electric utility and transportation sectors, as shown in Figure 3. Hydrogen can play an important role in a low-carbon global economy.

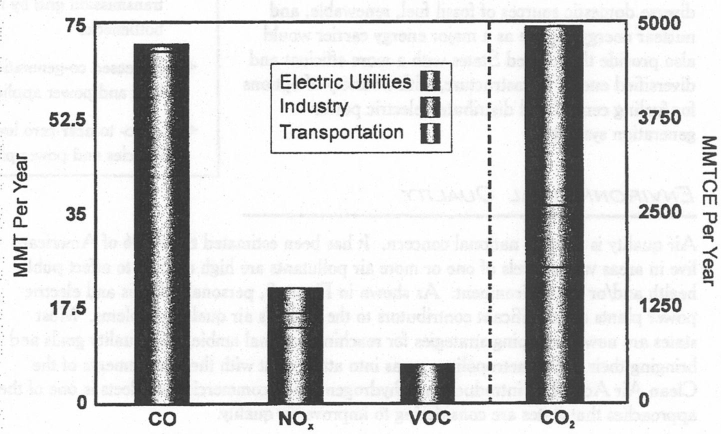
FIGURE 2. GROWING U.S. TRANSPORTATION OIL GAP



Source: Transportation Energy Data Book: Edition 22, September 2002, and *EIA Annual Energy Outlook 2003*, January 2003.

To reduce carbon emissions, hydrogen production from coal, natural gas, and oil with the capture and sequestration of carbon can provide a way for domestic fossil fuels to remain viable energy resources. Fuel cells operating on hydrogen produced and distributed solely from renewable resources or nuclear energy result in near-zero carbon emissions.

FIGURE 3. EMISSIONS FROM FOSSIL FUEL COMBUSTION



Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000, *EPA-430-R-02-003, April 2002.*

GLOBAL LEADERSHIP

It is clear that there is growing worldwide interest in hydrogen and fuel cell technology, as reflected in the dramatic increase in public and private spending since the mid-1990s in the U.S. and other countries. The U.S. government spends about $300 million annually on hydrogen and fuel cell programs, more than any other country in the world. A subset of these programs - - those that can directly contribute to the President's vision of commercially-viable hydrogen fuel cell vehicles by 2015 - - comprise the Hydrogen Fuel Initiative. These programs have already begun to see significant funding increases as part of the President's commitment to request $1.2 billion over five years for these activities. In addition, private sector spending on these activities in the U.S. is generally greater than in other countries. Thus, the U.S. is clearly a leader. Other countries are increasing investment as well. In 2003, the Japanese government nearly doubled its fuel cell R&D budget to $268 million, from $184 million in 2002. In April 2003 Japan launched a joint government/industry demonstration of hydrogen fuel cell vehicles, including the deployment of more than seven new hydrogen refueling stations.[2] Governments and companies in Canada, Europe, and Asia are also investing heavily in hydrogen research, development and demonstration. For example, 10 new hydrogen refueling stations will be built in Europe over the next few years to fuel hydrogen-powered buses.

International Partnership for the Hydrogen Economy: Membership

Australia	India
Brazil	Italy
Canada	Japan
China	Norway
European Community	Republic of Korea
France	Russia
Germany	United Kingdom
Iceland	United States

The economic stakes are high – a recent report by PricewaterhouseCoopers projects global demand for all fuel cell products (in portable, stationary, and transportation power applications) to reach $46 billion per year by 2011 and to grow to more than $2.5 trillion per year in 2021.[3] The United States should strive to continue to be a global leader in hydrogen and fuel cell technology development and commercialization. To foster cooperation, Secretary of Energy Spencer Abraham called for an "International Partnership for the Hydrogen Economy" at the International Energy Agency Ministerial meeting in April 2003.

The partnership provides a mechanism to organize, evaluate and coordinate multinational research, development and deployment programs that advance the transition to a global hydrogen economy. Ministers from the sixteen members of the International Partnership for the Hydrogen Economy (IPHE) signed the IPHE Terms of Reference on November 21, 2003 at a ceremony held in Washington, D.C. The ministers were joined by more than 700 additional stakeholders from government, industry and the non-profit sector.

[2] *Fuel Cell Vehicles: Race to a New Automotive Future*, U.S. Department of Commerce, Office of Technology Policy, January 2003, p. 37.
[3] *Fuel Cells: The Opportunity for Canada*, PricewaterhouseCoopers, June 2002, 68p.

3. Overview of the Transition to a Hydrogen Economy

Hydrogen energy development is one of the Department's top priorities. The President's Hydrogen Fuel Initiative calls for an increasing federal commitment to R&D that will accelerate industry's ability to make a commercialization decision on hydrogen-based transportation technologies. The *National Hydrogen Energy Roadmap*, released by Secretary Abraham on November 12, 2002, and the supporting hydrogen *Vision*, provide a guide for the Department's efforts. The sections below summarize some of the highlights of the *Vision* and *Roadmap* and describe key elements of the transition process.

Technology Readiness of Hydrogen

Although hydrogen is the most abundant element in the universe, it must be produced from other hydrogen-containing compounds such as fossil fuels, biomass, or water. Each method of production requires a source of energy, i.e., thermal (heat), electrolytic (electricity), or photolytic (light) energy. Hydrogen is either consumed on site or distributed to end users via pipelines, trucks, or other means. Hydrogen can be stored as a liquid, gas, or chemical compound and is converted into energy through fuel cells or by combustion in turbines and engines. Fuel cells now in development will not only provide a new way to produce power, but will also improve energy conversion efficiency, especially in transportation applications.

The U.S. chemical and refining industries have a limited number of commercial facilities in place for the production and delivery of hydrogen (about nine million tons is manufactured annually for use in these industries). Those operations are localized, and cannot provide the technology advances and carbon management required for widespread use of hydrogen in the energy sector (i.e., large-scale, low-cost production methods, and storage and delivery infrastructures compatible with automotive and distributed generation applications). Currently, technical challenges remain (centered around cost, performance, and safety) in the elements of the hydrogen energy infrastructure shown in Figure 4. Addressing these challenges will require a coordinated, multi-agency effort. More detailed information on the status of hydrogen technology today and the associated challenges is provided in the National Hydrogen *Vision* and *Roadmap*.

Long-Term Vision of the Hydrogen Economy

In the long-term vision of the hydrogen economy (which will take several decades to achieve), hydrogen will be available in all regions of the country and will serve all sectors of the economy. It will be produced from fossil fuels (with carbon capture and sequestration), renewable energy, and nuclear energy. It will be used throughout the transportation, electric power, and consumer sectors. Hydrogen will be produced in centralized facilities, in distributed facilities at power parks, fueling stations, rural areas, and community locations. Hydrogen production and storage costs will be competitive; the basic components of a national hydrogen delivery and distribution network will be in place; and hydrogen-powered fuel cells, engines, and turbines will have become mature technologies in mass production for use in cars, homes, offices, and factories.

FIGURE 4. HYDROGEN ENERGY SYSTEM ELEMENTS AND CHALLENGES

HYDROGEN VISION ELEMENTS	KEY TECHNICAL CHALLENGES
PRODUCTION Hydrogen will be centrally produced in large refineries, energy complexes, or at renewable or nuclear power facilities, and locally produced in power parks, fueling stations, communities, rural areas, and on-site at customers' premises. Thermal, electric, and photolytic processes will use fossil fuels, biomass, or water as feedstocks and release little or no carbon dioxide into the atmosphere.	◆ Low cost hydrogen production techniques ◆ Low cost and environmentally sound carbon capture and sequestration technologies ◆ Advanced hydrogen production techniques from fossil fuels, renewable, and nuclear resources
DELIVERY A national supply network will evolve to accommodate both centralized and decentralized production facilities. Pipelines will distribute hydrogen to high-demand areas. Trucks and other means will distribute hydrogen or liquid or solid hydrogen carriers to rural and other lower-demand areas.	◆ Lower-cost hydrogen transport technology ◆ Appropriate codes and standards ◆ Right of way for new delivery systems
STORAGE A selection of relatively lightweight, low-cost, and high storage density (low-volume) hydrogen storage devices will be available in a variety of sizes to meet different energy needs.	◆ Low cost, light weight, and energy dense storage systems
CONVERSION Fuel cells will be a mature, cost-competitive technology in mass production. Advanced, hydrogen-powered energy conversion devices such as combustion turbines and reciprocating engines will enjoy widespread commercial use.	◆ Low cost, durable, and reliable fuel cells that can be mass produced
APPLICATIONS Hydrogen will be available for every end-use energy need in the economy, including transportation, central and distributed electric power, portable power, and combined heat and power for buildings and industrial processes.	◆ Successful field tests and demonstrations ◆ Supportive public policies to stimulate infrastructure and market readiness
CODES AND STANDARDS/EDUCATION AND SAFETY Two families of model building codes will be published and available for adoption by local jurisdictions that reference comprehensive equipment standards for hydrogen and fuel cell technologies for commercial and residential applications.	◆ Published fuel gas code that includes hydrogen ◆ Published safety standard for certification of a fuel cell vehicle ◆ Insurance rating of hydrogen energy systems ◆ Training and certification program for code and building officials

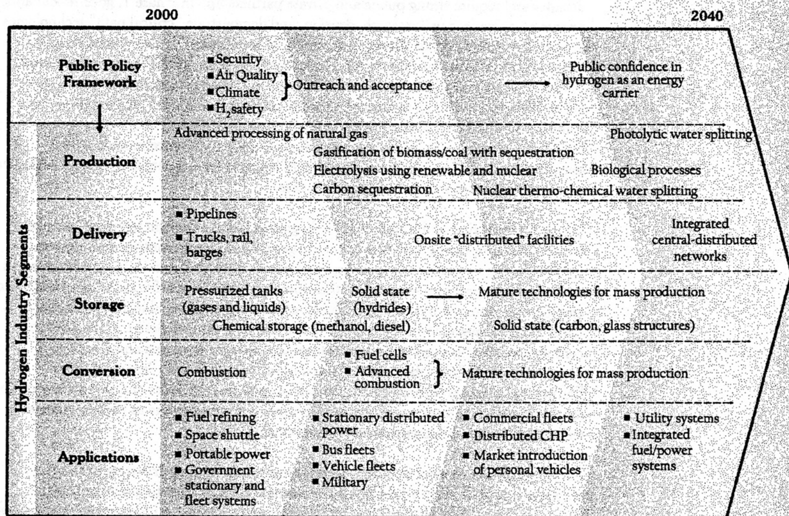
Hydrogen will be the dominant fuel for government and transit bus fleets. It will be used in personal vehicles and light duty trucks. Hydrogen will be combusted directly in turbines and reciprocating engines to generate electricity and thermal energy for homes, offices, and factories. It will be used in fuel cells for both mobile and stationary applications. U.S. companies that commercialize hydrogen technologies will be exporting products and services around the world. Developing countries will have access to clean, sustainable, economical hydrogen-based energy systems to meet their growing energy demands.[4]

GETTING FROM HERE TO THERE

Achieving this vision will require a combination of technological breakthroughs, market acceptance, and large investments in a national hydrogen energy infrastructure. Success will not happen overnight, or even over years, but rather over decades; it will require an evolutionary process that phases hydrogen in as the technologies and their markets are ready. Figure 5 presents one way in which this transition might occur.

[4] *A National Vision of America's Transition to a Hydrogen Economy to 2030 and Beyond*, U.S. DOE, February 2002.

Figure 5. Transition to the Hydrogen Economy



In the near- to mid-term, most hydrogen will likely be produced by technologies that do not require a new hydrogen delivery infrastructure – i.e., from distributed natural gas and electrolysis of water using electricity (with emphasis on renewable sources such as wind power). As research, development and demonstration (RD&D) efforts progress along renewable, nuclear, and clean coal and natural gas production pathways, a suite of technologies will become available in the mid- and longer-term to produce hydrogen from a diverse array of domestic resources. The economic viability of these different production pathways (samples of which are shown in Appendix A) will be strongly affected by regional factors, such as feedstock availability and cost, delivery approaches, and regulatory environment.

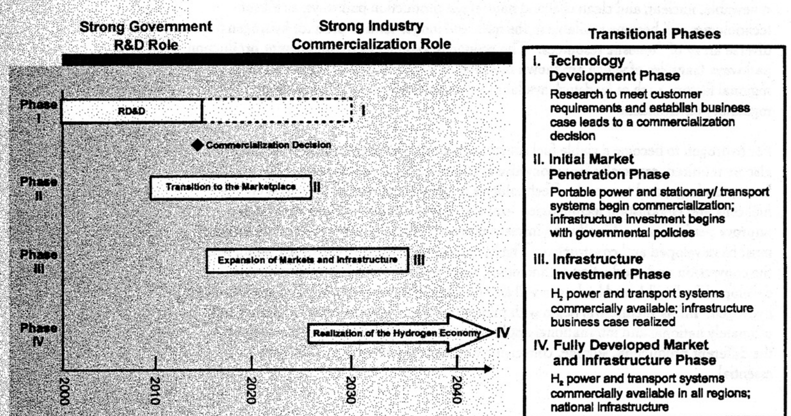
For hydrogen to become a viable fuel source, advanced hydrogen storage technologies will also be required, especially for automotive applications. Current storage systems are too heavy, too large, and too costly. Technologies to convert hydrogen into useful energy—fuel cells and combustion technologies—must be further improved to lower cost and improve performance. Finally, the infrastructure to deliver hydrogen where it is needed must be developed and constructed. The hydrogen infrastructure can evolve along with the conversion and production technologies, since most of the infrastructure that is developed for fossil-based hydrogen will also be applicable to renewable- and nuclear-based hydrogen. Infrastructure will begin with pilot projects and expand to local, regional, and ultimately national and international applications. More detailed economic analyses of the different production, storage, conversion and distribution options will also be essential.

As shown in Figure 6, a full transition to a hydrogen-based energy system will take several decades and require strong public and private partnership. In Phase 1, government and private organizations will research, develop, and demonstrate "critical path" technologies and safety assurance prior to investing heavily in infrastructure. Public education and codes and standards must be developed concurrently with the RD&D. The President's Hydrogen Fuel Initiative is consistent with completion of the critical path technology RD&D phase leading up to a commercialization decision in 2015. This Phase could continue beyond 2015 to support basic science and to further develop advanced, sustainable technologies for hydrogen production and use. The commercialization decision criteria will be based on the ability of hydrogen fuel technology to meet customer requirements and to establish the business case.

Phase II, Transition to the Marketplace, begins as industries begin to manufacture and market hydrogen (using the existing natural gas and electric grid infrastructure) and fuel cell technologies in portable, stationary, and transportation applications. Consumers will need compelling reasons to purchase these products; public benefits such as high efficiency and low emissions are not enough. The all-electronic car powered by hydrogen fuel cells (such as the General Motors Hy-wire) is one example of value delivery; it offers the consumer much improved performance through elimination of mechanical parts and greater design flexibility through the "skateboard" approach with "snap-on" bodies. During this phase, government agencies will work to develop codes and standards required for the transition. Government and industry involvement continue as hydrogen-related technologies meet or exceed customer requirements.

As these markets become established, government can foster their further growth by playing the role of "early adopter" and by creating policies that stimulate the market. Phase III, Expansion of Markets and Infrastructure, proceeds if industry makes a positive commercialization decision in 2015. During this phase the business case for a hydrogen-

FIGURE 6. GOVERNMENT-INDUSTRY ROLES IN THE TRANSITION TO A HYDROGEN ECONOMY



based economy is realized, attracting investment in infrastructure for fuel cell manufacturing and hydrogen production and delivery. Government policies still may be required to nurture this infrastructure expansion phase. Phase IV, several decades from now, is Realization of the Hydrogen Vision, when consumer requirements will be met or exceeded, national benefits in terms of energy security and improved environmental quality are achieved, and industry can receive adequate return on investment and compete globally.

4. DOE Hydrogen Program

Program Mission

The central mission of the DOE's Hydrogen Program is to research, develop, and validate fuel cell and hydrogen production, delivery, and storage technologies. Hydrogen from diverse domestic resources will then be used in a clean, safe, reliable, and affordable manner in fuel cell vehicles and stationary power applications. Development of hydrogen energy will ensure that the United States has an abundant, reliable, and affordable supply of clean energy to maintain the Nation's prosperity throughout the 21st century.

Program Strategy

DOE is currently conducting research, development, demonstrations, standards formulation, and public outreach and education activities. These activities are carried out in partnership with automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, other federal agencies, state government agencies, universities, national laboratories, and other stakeholder organizations.

These activities address the development of hydrogen energy systems for transportation, stationary power, and portable power applications. Stationary power applications include combined heat and power generation systems in buildings and manufacturing facilities, utility-scale power systems, and distributed (smaller-scale) power systems. Transportation applications include fuel cell and hydrogen infrastructure development. DOE-funded activities include cost-shared, public-private partnerships to address the high-risk, critical technology barriers preventing widespread use of hydrogen as an energy carrier. These efforts are augmented by fundamental and applied research at national laboratories and universities.

DOE is funding RD&D efforts that will provide the basis for the near-, mid-, and long-term production, delivery, storage, and use of hydrogen derived from fossil fuel, nuclear, and renewable sources. Reforming of distributed natural gas and electrolysis will be the most efficient and economical way to produce hydrogen for near-term applications, but costs are still too high.

As reflected in the Administration's FutureGen project (also known as the Integrated Sequestration and Hydrogen Research Initiative), technologies will continue to be evaluated and developed to produce low-cost hydrogen from domestic and secure sources of coal with the capture and sequestration of CO_2. With the implementation of carbon management strategies, coal will play a key role in the long term because of its abundance and low cost. Hydrogen from renewable biomass feedstocks can benefit from gasification, reforming, and separation technologies developed for fossil resources. The production of hydrogen from non-conventional sources such as biological materials will be explored through fundamental basic science.

To address the need for sustainable energy supplies, DOE is also investigating advanced methods of hydrogen production from renewable and nuclear resources, and more advanced systems for storing and delivering hydrogen in an expanded hydrogen market.

The DOE will focus on methods to produce affordable supplies of hydrogen from water using renewable electricity (e.g., solar, wind) and nuclear sources of energy, or even using direct solar conversion or biological methods. A mix of diverse energy feedstocks to produce hydrogen is needed to gradually make the transition to a sustainable, secure, affordable, and environmentally safe hydrogen energy system.

FY05 Program Activities and Highlights

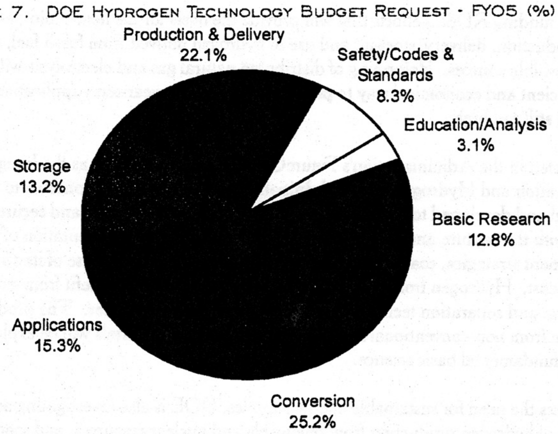
The DOE Hydrogen Program funds efforts in the following areas, which support the National Hydrogen Energy *Vision* and *Roadmap*.

- Production and Delivery
- Storage
- Conversion
- Basic Research
- End-use Applications
- Education/Systems Analysis
- Safety/Codes and Standards

These areas are necessarily interrelated, with developments in one segment relying on corresponding developments in other segments. An integrated approach to RD&D within the Department will ensure that, regardless of the pathway, common challenges are efficiently addressed. Figure 7 shows how the DOE budget request for FY05 breaks out into the program areas.

Associated RD&D includes efforts that are necessary to achieve a hydrogen energy pathway (e.g., high-temperature stationary fuel cells, carbon sequestration and carbon management, hybrid electric vehicle research as part of the FreedomCAR partnership,

Figure 7. DOE Hydrogen Technology Budget Request - FY05 (%)



TOTAL: $227 Million

and coal and biomass gasification), but which are likely to be funded even if there were no DOE hydrogen program. The President's Hydrogen Fuel Initiative reflects an enhanced hydrogen and fuel cell program to accelerate technology development and demonstration activities. This enhanced program will facilitate commercialization decisions by industry in the year 2015, allowing rapid market penetration and significant oil displacement and environmental benefits for the year 2030 and beyond. The budget includes an increasing emphasis on exploratory research for hydrogen production, storage, and end use applications. RD&D on hydrogen conversion continues at essentially steady levels, with some shifts to increase or decrease emphasis on particular technologies or pathways. Ongoing work in two important DOE-industry partnerships continues: FreedomCAR and the Solid State Energy Conversion Alliance (SECA).

The following sections provide an overview of key DOE FY05 hydrogen activities in production, delivery, storage, conversion, basic research, applications and education, and safety/codes and standards.

Production and Delivery

- ✦ Conduct research on lowering costs of distributed hydrogen production from natural gas, including:
  - Membranes
  - Catalytic hot oxygen reactor
- ✦ Conduct coal-derived hydrogen program.
  - Continue computational science and research studies on advanced systems for producing hydrogen from liquid carriers
  - Research to develop advanced separation, cleanup and process intensification technology to produce lower-cost hydrogen
  - RD&D to integrate carbon capture and sequestration technologies into fossil-based production systems
- ✦ Accelerate and expand research on the production of hydrogen from renewable resources including
  - Electrolysis cost reduction
  - Thermochemical conversion of biomass
  - Photolytic and fermentative micro-organism systems
  - Photoelectrochemical systems and water electrolysis
  - High-temperature chemical cycle water splitting and other non-carbon emitting high temperature technology
- ✦ Conduct research to develop a multi-fuel, oxygen-blown, integrated gasification combined cycle system that can produce hydrogen and power.

Fossil Energy Focuses on Hydrogen From Coal

The Office of Fossil Energy (FE) will build upon ongoing RD&D activities within FE to demonstrate low-cost, novel, and advanced hydrogen production and delivery technologies from coal by 2015. These technologies include advanced shift and separation technologies including membranes for producing hydrogen from coal, cost- effective removal of carbon dioxide and trace components, and optimal synthesized gas-derived liquid fuels for fuel cell applications. Integration of these technology modules into advanced coal power plants will allow production of affordable hydrogen from domestic fossil energy with essentially zero air emissions.

FutureGen: Emission-Free, Coal-Fired Electricity and Hydrogen Production

On February 27, 2003, President Bush announced that the United States would sponsor a $1 billion, 10-year initiative to create the world's first coal-based, zero emissions power plant to produce electricity and hydrogen. In support of this announcement, Secretary of Energy Abraham unveiled plans for a new DOE initiative called FutureGen. This project will establish the technical and economic feasibility of producing electricity and hydrogen from coal while capturing and sequestering the carbon dioxide generated in the process. FutureGen will be designed and constructed with the flexibility to conduct both full scale and slipstream tests of advanced technologies. These advanced technologies offer the promises of clean environmental performance at a reduced cost and increased reliability. FutureGen will showcase cutting-edge technologies that can virtually eliminate environmental concerns associated with coal utilization.

Nuclear Hydrogen Activities Will Harness Heat to Produce Hydrogen From Water

The Office of Nuclear Energy, Science & Technology will work with its partners to demonstrate the commercial-scale production of hydrogen using heat from a nuclear energy system by 2017. In addition to the emission-free electricity currently produced by nuclear reactors, some advanced nuclear reactor designs operate at very high temperatures, making them well-suited to drive highly efficient hydrogen production processes. Several reactors selected for further research and development under the Generation IV Nuclear Energy Systems Initiative (GenIV) are capable of high-efficiency hydrogen production.

The Solid State Energy Conversion Alliance (SECA) Will Fast-Track Commercialization of Solid Oxide Fuel Cells

SECA is a joint government-industry effort to achieve cost and technology breakthroughs in solid oxide fuel cell (SOFC) development within a short period of time. The goal is to create a solid oxide fuel cell (3-10 kW) that can be mass produced in modular form. Used individually or in clusters, depending upon the amount of energy required, these fuel cells will be able to power a broad array of applications. Identified technical challenges include: fuel processing and manufacturing; controls and diagnostics; power electronics; modeling and simulations; and materials. A five- to ten-fold cost reduction over existing technology is required to reach the goal of producing SOFCs at a cost of $400/kW. Key milestones include:

2010: Demonstrate 3-10kW fuel cells at $400/kW with target efficiencies of 40-60%.

2015: Demonstrate hybrid fuel cell/turbines that meet $400/kW system requirements with 70-80% efficiencies.

- ✦ Initiate Nuclear Hydrogen Initiative.
  - Issue Nuclear Hydrogen R&D Plan
  - Begin R&D on baseline hydrogen production processes (high-temperature electrolysis and sulfur-based thermochemical cycles)
- ✦ Conduct research to develop technology for gas/liquids produced from biomass to supply cost-effective renewable-based hydrogen.
- ✦ Conduct research to lower the cost and improve the energy efficiency of hydrogen compression and liquefaction.
- ✦ Conduct research to lower the cost of hydrogen delivery infrastructure, including development of improved, lower cost materials for hydrogen pipelines and new liquid or solid hydrogen carriers.

Storage

- ✦ Complete research, including materials work, to validate high-pressure and cryogenic tanks for near-term approaches.
- ✦ Emphasize research and evaluation of innovative storage approaches including reversible storage materials, such as carbon nanotubes and metal hydrides; regeneration issues related to chemical hydrides; and options for hybrid approaches that combine compressed gas storage with reversible materials.

Conversion

- ✦ Continue RD&D to lower cost and improve durability of polymer electrolyte membrane fuel cell for transportation and small stationary applications.
- ✦ Initiate development of auxiliary power unit systems for heavy vehicle application.
- ✦ Downselect for further development and demonstrate baseline performance of high temperature membranes.

Basic Research

- ✦ Conduct research in novel materials for hydrogen storage with major research components in complex hydrides; nanostructured materials; theory, modeling, and simulation approaches; and novel analytical and characterization tools.

✦ Investigate membrane materials for separation, purification, and ion transport to include major research programs in integrated nanoscale architectures; fuel cell membranes; and theory, modeling, and simulation of separation processes and mechanisms.

✦ Design of catalysts at the nanoscale with the main emphasis on nanoscale phenomena; innovative synthetic techniques; novel characterization techniques; and theory, modeling, and simulation of catalytic pathways.

✦ Investigate bio-inspired materials and processes to include studies of enzyme catalysts; bio-hybrid energy coupled systems; and theory, modeling and nanostructure design.

✦ Conduct research to explore solar energy-based hydrogen production with the emphasis on nanoscale structures; light harvesting and novel photoconversion concepts; organic semiconductors and other high performance materials; and theory, modeling, and simulation of photochemical processes.

Basic Research Will Target Breakthroughs in Key Areas

Recent advances in nanosciences, catalysis, modeling, simulation, and bio-inspired approaches offer exciting new research opportunities for addressing both short-term showstoppers and long-term grand challenges to the practical realization of a hydrogen economy. DOE's Office of Science seeks to foster revolutionary advances in hydrogen production, delivery, storage, and conversion technologies in the following five critical basic research areas: Novel Materials for Hydrogen Storage; Membranes for Separation, Purification, and Ion Transport; Design of Catalysts at the Nanoscale; Bio-Inspired Materials and Processes; and Solar Hydrogen. The basic hydrogen research program will be coordinated with the needs of applied research and development, and will employ coupled experimental and theoretical components for maximum impact. The integration will ensure that discoveries and related conceptual breakthroughs achieved in basic research programs will provide a foundation for the innovative design of materials and processes that will produce improvements in the performance, cost, and reliability of hydrogen production, storage, and use. For more information on how basic research can help overcome technical challenges to a hydrogen economy, see the recent Basic Energy Sciences report at http://www.sc.doe.gov/bes/hydrogen.pdf.

Applications

✦ In collaboration with DOT and EPA, conduct hydrogen infrastructure and fuel cells vehicle demonstration project to validate technology status and refocus RD&D.
  - Hydrogen fueling station safety, operations, reliability, and vehicle interface/fuel dispenser systems
  - Vehicle performance and reliability under real operating and climate conditions

✦ Validate safety and performance data from power park systems to co-produce hydrogen and electricity for vehicles and grid, respectively.

Education and Safety/Codes and Standards

✦ Implement training program for elementary and secondary school teachers.

✦ In coordination with DOT, conduct educational campaign to communicate hydrogen benefits, safety, and utilization information to key stakeholders.

✦ In coordination with the DOT, conduct top-down safety analysis of all hydrogen-related processes and equipment for transportation and stationary applications and begin identifying design requirements.

✦ In coordination with the DOT, assist national and international code developers in developing new building codes and equipment standards.

✦ Implement comprehensive safety testing and evaluation program for hydrogen fuel cell vehicles, in collaboration with DOT, EPA, NIST and other agencies.

✦ Develop comprehensive economic model to analyze technology options and tradeoffs.

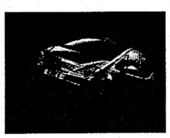
FreedomCAR Aims to Overcome Hydrogen-Powered Fuel Cell Research Hurdles

FreedomCAR is a government-industry partnership between the U.S. Department of Energy and the U.S. Council for Automobile Research (members include Ford Motor Company, General Motors Corporation, and DaimlerChrysler Corporation). The collaboration was formed to jointly research high-efficiency, clean cars as part of an effort to reduce American dependence on foreign oil. The C-A-R in FreedomCAR stands for Cooperative Automotive Research.

The long-term strategic goal of FreedomCAR participants is to develop technologies for hydrogen-powered fuel cell vehicles that are not dependent on oil and emit no harmful pollutants or greenhouse gases. The aim is to achieve this technology shift without sacrificing mobility or freedom of choice for American consumers. In the near term, FreedomCAR will support a wide range of hybrid electric vehicle technologies that are designed to reduce oil consumption and vehicle tailpipe emissions.

Participants will work together to develop technologies that will eventually enable the mass production of affordable hydrogen-powered fuel cell vehicles and the hydrogen infrastructure to support them. The Partnership Plan identifies technology milestones to measure progress in 2010 and 2015 (these can be downloaded from www.eere.energy.gov/vehicle.html). Some of the key 2010 milestones include:

- Electric propulsion system with a 15-year life and capability to deliver at least 55 kW for 18 seconds, and 30 kW continuously at a system cost of $125/kW peak.
- Internal combustion engine powertrain systems that cost $30/kW, have a peak brake engine efficiency of 45%, and meet or exceed emission standards.
- Electric drivetrain energy storage with a 15-year life at 300Wh and with a discharge power of 25 kW for 18 seconds at a cost of $20/kW.
- Material and manufacturing technologies for high-volume production vehicles that enable/support the simultaneous attainment of affordability, increased use of recyclable/renewable materials, and a 50% reduction in the weight of the vehicle structure and subsystems.



DaimlerChrysler NECAR5

Ford P2000 Prodigy

GM HydroGen1

PROGRAM MILESTONES

The milestone chart shown in Figure 8 presents the key activities of DOE's Hydrogen Program through completion of the critical path technology development phase in 2015. Technology development is projected to continue beyond 2015 to support basic science and RD&D on advanced technologies and renewable hydrogen production alternatives. The milestones are organized according to the National Hydrogen Energy Vision and Roadmap's six key elements.

Milestones for each of the timelines specify a delivery date for the given technology development, improvement, or demonstration. The values given are compiled from the best available primary sources, including DOE analysis, the FreedomCAR Partnership Plan, the National Hydrogen Energy Roadmap, and ongoing Federal laboratory research. As technologies evolve and economic and systems analyses progress, these targets will be refined.

The milestones listed in Figure 8 describe DOE hydrogen RD&D activities at a high level of aggregation and may not articulate all component activities represented by the milestone. The timelines do not list all of the interim milestones for each pathway, nor do they include every critical go/no-go decision point and technology option downselect point integral to each activity at the sub-program and project level. Some production technologies, such as photoelectrochemical, may require longer development beyond 2015 to be cost-competitive with other hydrogen production methods.

For each milestone in Figure 8, the most appropriate measurement units are provided in the legend. For some technologies, costs are primarily associated with scale (e.g., dollars per megawatt of capacity); for others, costs are associated with delivered hydrogen (e.g., dollars per gallon of gasoline equivalent, or gge). The term "project to" means that the technology demonstrated at the indicated time point would meet the specified cost target if that technology were in full commercial-scale production.

BUDGET OUTLOOK

The President's Hydrogen Fuel Initiative will put the program on track to meet the 2015 milestones listed here.

As technical milestones are achieved, DOE will need to invest resources to overcome barriers to commercialization and infrastructure development. An increased focus on educating consumers about the safe use of hydrogen and its benefits will be essential to enhance awareness and acceptance of the technology. Detailed analysis of life-cycle costs and benefits and environmental impacts will continue to support decisions regarding future hydrogen related research.

Out-year planning will identify needs to expand RD&D on production and storage technologies, delivery infrastructure, and education and safety/codes and standards. The $1.2 billion Hydrogen Fuel Initiative proposed by President Bush for 2004-2008 includes $720 million in new R&D funding. Some specific activities that would be pursued with this funding in the next five fiscal years include:

Production – Lowering production costs is a top priority. A National Academies' study, requested by DOE and just completed, provides insight for a hydrogen feedstock

FIGURE 8. TECHNOLOGY DEVELOPMENT TIMELINE (PHASE I): MILESTONES AND DECISION POINTS

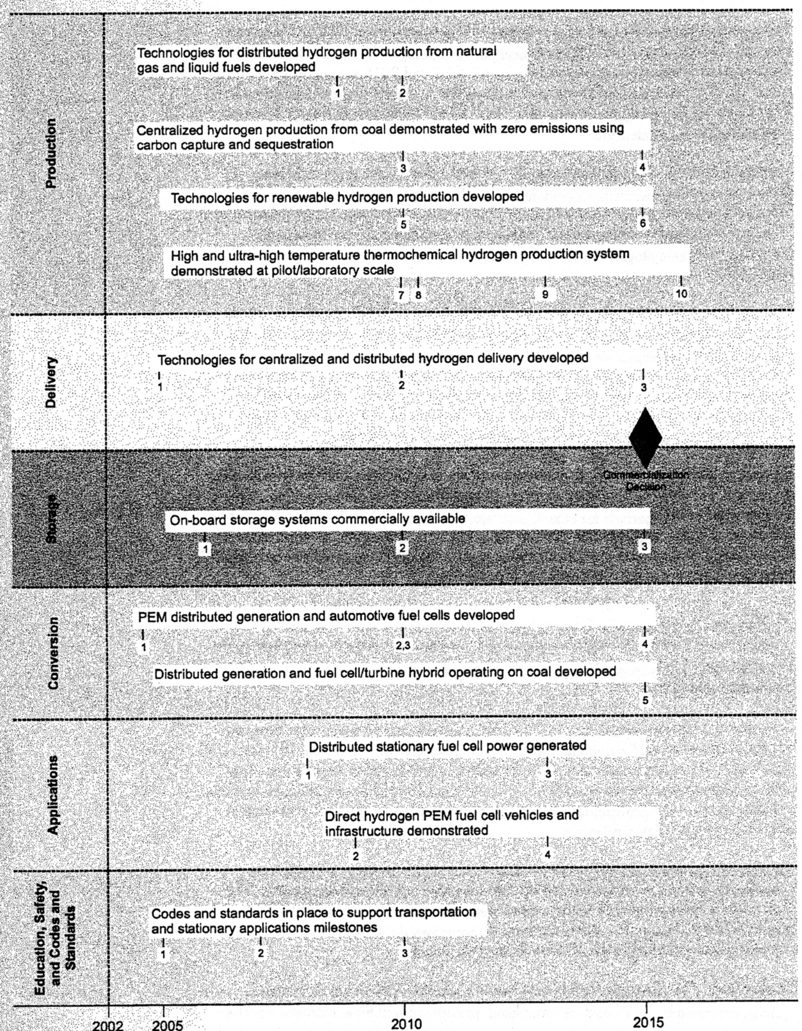


FIGURE 8 (CONT'D). LEGEND FOR TECHNOLOGY DEVELOPMENT TIMELINE (PHASE I)

Production Milestones

Distributed Natural Gas/ Liquid Fuels*

1. 2009: Develop technology to produce distributed hydrogen from natural gas or liquid fuels at a refueling station that projects to a cost of $2.50/gge for hydrogen. [At the pump, untaxed, no carbon sequestration]
2. 2010: Develop technology to produce hydrogen from natural gas or liquid fuels at a refueling station that projects to a cost of $1.50/gge for hydrogen. [At the pump, untaxed, no carbon sequestration, at 5000 psig]

Central Coal*

3. 2010: Develop pilot scale membrane separation and reactive/membrane separation technology for hydrogen production that meets cost targets.
4. 2015: Demonstrate a zero emission coal plant producing hydrogen and power with carbon capture and sequestration at a 25% cost reduction that projects to $0.80/gge at the plant gate ($1.80/gge delivered).

Renewable Resources

5. 2010: Develop technologies for integrated wind hydrogen production at $2.85/gge delivered assuming a 500 gge/day electrolyzer system and $0.04/kWh wind electricity (2015: $2.25/gge).
6. 2015: Demonstrate laboratory-scale biological system to produce hydrogen at a cost that projects to $10/gge at the plant gate ($11/gge delivered). Demonstrate laboratory-scale photoelectrochemical water splitting at a cost that projects to $5/gge at the plant gate ($6/gge delivered). The long term goal for these hydrogen production technologies is to be competitive with gasoline.

High-Temperature Thermochemical

7. 2010: Laboratory-scale demonstration of ultra-high-temperature thermochemical hydrogen production from solar reactors that project to a cost of $2.50/gge ($3.80/gge delivered).
8. 2011: Pilot-scale demonstration of high-temperature thermo-chemical production for use with nuclear reactors that projects to a cost of $2.50/gge ($3.50/gge delivered).
9. 2013: Design of engineering scale nuclear hydrogen production system completed.
10. 2017: Engineering-scale demonstration of thermochemical hydrogen production system with cost that projects to less than $2.00/gge at the plant gate ($3/gge delivered) using heat from nuclear reactors.

Storage Milestones

1. 2006: Downselect hydrogen storage options with potential to meet 2010 targets.
2. 2010: Develop and verify on-board storage systems achieving: 6% by weight capacity and 1500 watt hours/liter energy density at a cost of $4.00/kWh of stored energy.
3. 2015: Develop and verify on-board storage systems achieving: 9% by weight capacity, 2700 watt hours/liter, and $2.00/kWh.

Applications Milestones

1. 2008: Validate first regional networks with fuel cell systems that project a cost of less than $1,250/kW.
2. 2009: Direct hydrogen polymer electrolyte membrane fuel cell vehicles demonstrated at multiple sites, achieving 2,000 hours durability.
3. 2013: Validate stationary fuel cell system that co-produces hydrogen and electricity at 40,000 hours durability with 40% efficiency at a cost of $750/kW or less.
4. 2013: Validate direct hydrogen polymer electrolyte membrane fuel cell vehicles achieving 5,000 hours durability (service life of vehicle) and 300 mile range.

◆ **Phase 1 Commercialization Decision: 2015**

Based on technology development success in meeting customer requirements and establishing a business case.

Conversion Milestones

1. 2004: On-board fuel processing Go/No Go decision based on ability to achieve 78% efficiency and <0.5 minute start time.
2. 2010: Distributed stationary generation natural gas/ propane 50-250 kW fuel cell developed: 40% electrical efficiency, 40,000 hours durability (equivalent to service life between major overhauls), at a cost of less than $400-$750/kW.
3. 2010: Develop direct hydrogen polymer electrolyte membrane automotive fuel cell operating at 60% peak efficiency, 220 W/L density, 325 W/gge specific power at a cost of $45/kW (automotive production quantity).
4. 2015: Polymer electrolyte membrane automotive fuel cell meets cost of $30/kW.
5. 2015: Fuel cell/turbine hybrid operating on coal developed at a cost of $400/kW with a system efficiency of 70% with carbon sequestration.

Education, Safety, and Codes and Standards Milestones

1. 2005: Publish codes and standards models and safety and training materials.
2. 2007: Education program on safety in place.
3. 2010: Technical codes and standards in place to support regulatory standards.

Delivery Milestones

1. 2005: Define a cost-effective hydrogen fuel delivery infrastructure for supporting the introduction and long-term use of hydrogen for transportation and stationary power.
2. 2010: Develop technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use in vehicles or stationary power units to <$1.30/gge of hydrogen.
3. 2015: Develop technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use in vehicles or stationary power units to <$1.00/gge of hydrogen.

* *The assumed feedstock cost for natural gas is $4.00/million Btu and the assumed cost for coal is $29.00/short ton.*

strategy for the transition and long term. The study will help DOE set priorities for research needs in out-year planning.

The development of small-scale natural gas reformer and electrolysis technologies are needed as part of the transition to the market place. Development efforts are required for natural gas-to-hydrogen generation technologies that can be mass-produced and operated reliably and safely in a typical fueling station with remote operations control to reduce costs. Technologies using partial oxidation (or autothermal reforming) and steam methane reforming processes should be further developed for high energy efficiencies. In electrolysis technology, reduced capital costs, enhanced system efficiency, and improved durability for distributed-scale hydrogen production from renewable-sourced electricity and water is needed. Lower-cost membranes and catalysts that can operate at higher temperatures and pressures need development as well as improved system integration to lower the cost of manufacturing. Emphasis is needed in component development and systems integration to enable electrolyzers to operate from inherently intermittent and variable-quality power derived from wind and solar sources. The aim is to partner with industry to create robust, efficient and cost-effective wind-electrolysis-hydrogen systems that will be ready for deployment as the distributed hydrogen infrastructure begins to develop.

The development of technologies and feedstocks for high-volume, efficient, centralized production of hydrogen is needed. For example, development efforts are required to simplify reforming processes using advanced catalysts and reactors; to develop durable membranes for separating hydrogen from coal-based syngas; and to develop high-temperature, thermochemical processes (e.g., sulfur-iodine) using solar and nuclear-generated heat. This latter activity could lead to the construction of an advanced demonstration nuclear plant with electricity and hydrogen co-production capabilities.

Basic research is needed to produce breakthroughs in catalysis and separations and to improve the understanding of carbon sequestration. Recent advances in nanoscale and molecular synthesis, such as characterization tools that allow active sites to be probed directly; modeling of complex chemical systems; and high-throughput synthesis and screening methods will support future catalyst research. A better understanding of light-induced dynamic processes in molecules, polymers, and semiconductor nanoparticles will support the development of low-cost solar cells and photocatalysts. Research on new semiconductors, polymers, supramolecular assemblies, and catalysts will enable the synthesis of two- and three-dimensional chemical systems for efficient light harvesting, charge separation, and fuel formation. These systems may also integrate biological or bio-inspired catalysts. Understanding the pathways by which hydrogen is made and processed in living organisms may enable breakthroughs by providing non-precious metal catalysts that allow fuel processing reactions to run at lower temperatures.

Additional areas of hydrogen production include novel and advanced systems such as advanced shift and separation devices including membranes for producing hydrogen from natural gas, coal, and biomass; cost-effective removal of carbon dioxide and trace components; and optimal synthesis gas-derived liquid fuels for decentralized reforming of hydrogen for fuel cell applications. Enhanced research on production of hydrogen from renewable resources (including conversion of biomass, photolytic and fermentative micro-organism systems, photoelectrochemical systems, and water electrolysis) will help to achieve the long term goal for cost-competitive hydrogen production from non carbon emitting domestic resources such as solar and wind energy.

Delivery – Delivery technologies and economics will heavily influence the level of infrastructure investment needed. Systems analysis of delivery alternatives will show the life-cycle cost advantages and disadvantages of transporting hydrogen over long distances and will identify areas in which cost reductions would provide the greatest value. New concepts will be needed to reduce delivery costs from the point of production to refueling stations and distributed power facilities. This effort could involve the development of lower-cost liquefaction technologies or the use of metal or chemical hydrides, carbon nanotubes, or other advanced hydrogen reversible liquid or solid carrier concepts that can increase the energy density of hydrogen transport. Existing natural gas pipelines could be used to carry a mixture of 20 percent hydrogen in natural gas. The main difference in a hydrogen pipeline grid compared to the existing natural gas pipeline is in the materials of construction. Efforts to ensure the safety of the hydrogen delivery system need to be coordinated with the Department of Transportation. In addition, low-cost compressor technology, pipeline materials, seals, components, and sensors and controls will be needed to lower the capital cost of hydrogen pipelines.

Storage – Lower cost, lighter weight, and higher density hydrogen storage is one of the key technologies needed for the hydrogen economy. A breakthrough in hydrogen storage could have tremendous impact. Advanced storage materials that show promise include alanates, carbon structures, chemical hydrides, and metal hydrides. As leading candidates for low- pressure, solid-state materials emerge, more intense efforts will need to be applied to this "critical path" technology area. Effort will be required to understand how to produce and contain these advanced materials, fill and discharge hydrogen, manage pressure and thermal properties, and integrate them into practical systems for stationary and mobile applications. The emphasis in basic research will be on understanding the chemical and physical processes governing the hydrogen-materials interactions to enable the design and discovery of new, higher efficiency, recyclable hydrogen storage materials. Research will take advantage of the revolutionary new properties and capabilities offered by nanoscience to further enhance storage capacity and to improve uptake/release kinetics. Improvements in today's metal and complex hydrides can be achieved by careful design of two- and three-dimensional nanoarchitectures to improve the weight percentages of stored hydrogen and provide control of hydrogen storage/release. Advances in basic science can also contribute to development of safe "smart" storage tanks that predict and communicate performance attributes and warn of potential failure.

Conversion – Cost reduction (by a factor of approximately 10) and improved durability and reliability will be required to assure the commercial viability of fuel cells in both stationary and mobile applications. Direct hydrogen conversion research will continue on high-efficiency polymer electrolyte membranes (PEM) and other fuel cell stack components and systems to meet cost, durability, power density, heat utilization, start-up time, cycling, load-following and other key performance targets. The high priority fundamental research topics include catalysts, electrochemistry, membranes, and the nanoscale behavior governing the performance and cost of fuel cells. The development of efficient and cost-effective fuel cell technology solutions for automotive and stationary applications presents a grand challenge that will take a substantial and sustained effort in chemical and materials research, combining both near- and long-term strategies. The major needs are all based on improved or new materials. Future efforts in on-board processing of hydrocarbon and alternative fuels to hydrogen will be guided by a major technology review in mid-2004 to assess the technical progress of research conducted to date on fuel processing systems.

Applications – Efforts are needed to demonstrate hydrogen energy systems (including fuel cells, engines, and turbines) in vehicles and distributed energy facilities. Demonstrations provide technical data for informing research programs as well as financial data for determining market and investment risks. Demonstrations are planned for a statistically significant number of hydrogen vehicles, including several locations and refueling stations. These demonstrations will be used to validate predictions of performance, cost, reliability, maintenance, and environmental impacts and to develop a better understanding of the vehicle and infrastructure. In stationary power facilities, demonstrations are needed on a statistically significant number of distributed heat and power systems. Early demonstrations could be conducted at federal facilities such as military bases, hospital complexes, and office buildings.

Codes and Standards – Commercialization of hydrogen technologies cannot proceed unless effective domestic and international codes and standards are in place. DOE, in collaboration with DOT, EPA, NIST, DOD, NASA, and other agencies, can play a role in fostering their development. Future efforts will include the development and dissemination of model building, fire, and safety codes; codes and standards for the hydrogen delivery infrastructure; utility interconnection and safety standards for hydrogen-fueled distributed energy devices; and product safety and performance standards and design requirements for vehicles, fuel cells, storage tanks, and other products and equipment that use hydrogen.

Education and Outreach – Consumer awareness and acceptance of hydrogen products and services will be an essential feature of the hydrogen economy. Federal and state officials, equipment manufacturers, users, and installation and maintenance personnel need to understand how to operate hydrogen technologies in a safe manner. Education and training materials for a variety of audiences need to be developed and disseminated. Target audiences include educators at the elementary, secondary, and university levels; code and zoning officials; professional and trade organizations; real estate developer and building owners and operators; public and private fleet operators; and the general public. These funds would be used to create a curriculum and training program for teachers and to develop educational materials for key target audiences.

Integrated Program Management and Coordination

The DOE Hydrogen Program currently includes participation from the Offices of Energy Efficiency and Renewable Energy (EE), Fossil Energy (FE), Nuclear Energy, Science and Technology (NE), and Science (SC). Each office manages activities that address hydrogen technologies that meet the needs of their respective feedstocks and target applications. As the nation focuses more attention and resources on exploring the potential for a hydrogen energy future, close coordination among these offices becomes critical.

One benefit of a hydrogen economy is its ability to use a diverse set of energy resources for supply. DOE's research activities will provide the United States with a variety of options for producing cost-competitive hydrogen. However, technical challenges associated with hydrogen storage, delivery, conversion, and end-use applications are the same regardless of whether the hydrogen is derived from a renewable, fossil, or nuclear pathway. Fuel cells are being designed to meet the unique needs of particular end-use applications (e.g., stationary generating stations and transportation systems), but these will ultimately be fueled with hydrogen from the energy feedstock mix that makes the most sense, both economically and environmentally, for a particular region.

A Program Management and Operations Plan will be developed to provide more detail on how DOE hydrogen activities will be managed and integrated within the Department. The Office of Energy Efficiency and Renewable Energy, as the lead organization for the President's Hydrogen Fuel Initiative, will designate the DOE Hydrogen Program Manager. Permanent working groups, such as the recently created Interagency Task Force and the DOE Hydrogen Working Group, will meet periodically to share information and coordinate activities. Recommended functions of the DOE Hydrogen Working Group (comprised of representatives of EE, FE, NE, and SC, as well as the Offices of Management, Budget and Evaluation and Policy and International Affairs) include:

- Evaluate the progress of the Department's hydrogen and related activities with regard to milestones and performance goals.
- Strengthen information exchange on technical developments.
- Help ensure that the various activities (e.g., budgeting, execution, evaluation, and reporting) remain well-coordinated.
- Provide suggestions for management improvements and stronger technical performance.
- Collaborate on systems analysis to understand the economic, energy, and environmental impacts of alternative technology pathways.

Program oversight and systems integration will be provided by the participating Assistant Secretaries or their equivalents reporting to the Under Secretary for Energy, Science and Environment. This group will monitor overall program costs, schedules, progress toward performance targets, and overlaps. The Hydrogen Technology Advisory Committee (HTAC), comprised of experts from industry, universities, and environmental groups, will continue to function in its role as a technical advisor to the Secretary. The Program Management and Operations Plan will describe how each of these organizational units will work together to ensure that the Department conducts its hydrogen research in a coordinated, focused, and efficient manner.

International cooperation and collaboration will also be important to efficiently achieve national hydrogen and fuel cell technology program goals. The Secretary has led the creation of an "International Partnership for the Hydrogen Economy" that establishes cooperative R&D efforts, common codes and standards, and the sharing of information necessary to develop a hydrogen fueling infrastructure.

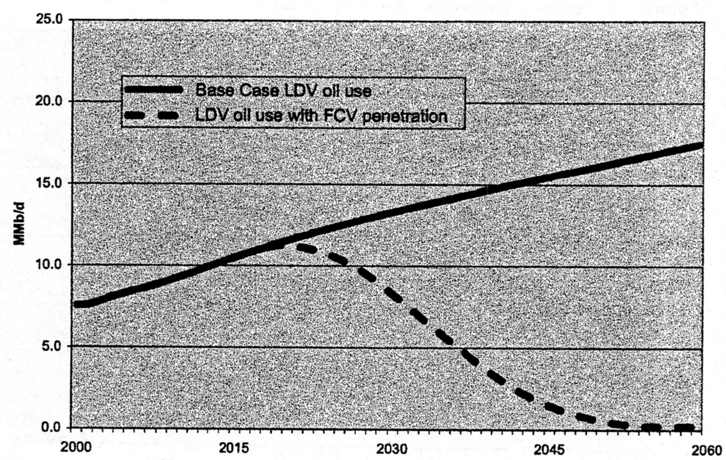
5. Potential Impacts on Oil Use and Greenhouse Gas Emissions

Expanded use of domestic resources to produce hydrogen will strengthen U.S. energy security and improve environmental quality. Achievement of hydrogen technology goals will pave the way for hydrogen's rapid growth as an energy carrier over the next several decades. The full extent of life-cycle cost and energy and environmental impacts will become clearer as technology development and validation progresses on the various production, conversion and distribution options. To illustrate the range of impacts, the remainder of this section presents some market penetration scenarios. Over the next two decades, conservation and high-efficiency petroleum-based vehicles can provide the greatest impact on reducing oil use and emissions.

TRANSPORTATION

Every day, eight million barrels of oil are required to fuel over 200 million vehicles that constitute our light-duty transportation fleet. The U.S. imports over half of the oil it consumes. Fuel cell vehicles could provide more than twice the efficiency of conventional vehicles and have the potential to reduce our dependence on oil while substantially

FIGURE 1O. OIL USE BY LIGHT DUTY VEHICLES



By 2040, light-duty vehicle oil consumption may be reduced by over 11 million barrels per day using hydrogen fuel cell vehicles.[6]

[5] The energy efficiency assumed for FCVs relative to conventional vehicles is 2.25 in 2018 and 2020, 2.5 in 2030 and 2040 and 3.0 beginning in 2050 with linear interpolation used for intervening years (assumes average new light duty vehicle fuel economy of 24.3 mpg for baseline vehicles).

[6] The penetration rate of FCVs in LDV sales is assumed to be 4% in 2018, 27% in 2020, 78% in 2030 and 100% by 2038 with linear interpolation for intervening years.

reducing emissions of air pollutants and greenhouse gases[5]. Figures 10 and 11 provide an example of the dramatic decrease in oil use and associated carbon emissions that could be realized by using hydrogen fuel cell vehicles.

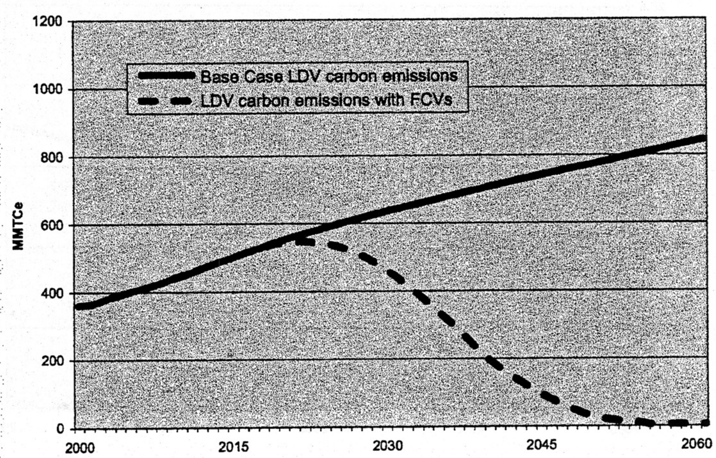
STATIONARY POWER

Hydrogen can be used in stationary fuel cells, engines and turbines to produce power and heat. In order to meet our growing electrical demands, it is estimated that electricity generation will have to increase by 2% per year[7]. At this rate, 1.5 trillion kWh of additional electricity generation capacity will be needed by 2020. As an example, if 10 million tons of hydrogen per year were used to provide 150 billion kWh of the nation's electricity (just 10% of the added generation), 20 million tons per year of carbon dioxide emissions could be avoided assuming the hydrogen is produced using renewables, nuclear, or fossil fuels with carbon capture and sequestration. Additional use of hydrogen technologies may be expected given aging infrastructure, requirements for reliable premium power, and market deregulation.

ENERGY DIVERSITY

Hydrogen can be supplied in large quantities from domestic fossil, nuclear and renewable resources. Hydrogen and fuel cells can increase the utilization of and establish a viable transportation market for nuclear energy, large domestic coal supplies, and renewables. Table 1 shows that our nation possesses the necessary resources to produce large quantities of hydrogen and begins to establish a picture of the required footprint for these production facilities.

FIGURE 12. CARBON EMISSIONS WITH FUEL CELLS



By 2040, light-duty vehicle carbon emissions may be reduced by more than 500 million metric tons of carbon equivalent each year using hydrogen fuel cell vehicles.[8]

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[7] U.S. DOE, Energy Information Administration, Annual Energy Outlook 2002

[8] Hydrogen is produced from natural gas or zero carbon fuels. The percentage from natural gas is assumed to be 93% in 2018, 90% in 2020, 55% in 2030, 15% in 2040, and 0% by 2050.

TABLE 1. HYDROGEN PRODUCTION FROM DOMESTIC RESOURCES SUMMARY

Examples of domestic resources that could be used to produce 40 million short tons of hydrogen to fuel 150 million vehicles (values shown are based on that resource being used to produce the full 40 million tons). The long-term strategy is to produce hydrogen from an array of diverse feedstocks. This analysis is only for perspective – currently 9 million short tons of industrial hydrogen are produced annually and 150 million vehicles is 75% of the light duty fleet. Note - The DOE Hydrogen Program is developing advanced technologies that could reduce these estimates of resource consumption and/or the footprint of these routes.

Resource	Needed for Hydrogen[a]	Availability	Current Consumption	Consumption with Hydrogen Production (factor times current)	Construction/ Footprint Required
REFORMING AND/OR PARTIAL OXIDATION[b]					
Natural Gas	95 million tons/year	28 billion tons (technically recoverable as of 1/2000)	475 million tons/year	1.2	400 dedicated hydrogen plants (100 MMSCF of hydrogen per day)
Biomass	400-800 million tons/year	800 million tons/year of biomass residue and waste, plus 300 million tons/year of dedicated crops[c]	200 million tons/year (3 quads for heat, power & electricity)	2-4	400-600 dedicated hydrogen plants
Coal	310 million tons/year	126 billion tons (recoverable bituminous coal)	1100 million tons/year (all grades)	1.3	280 dedicated hydrogen plants
WATER ELECTROLYSIS[d]					
Wind	555 GW_e	3250 GW_e	4 GW_e	140	Available capacity of North Dakota (Class 3 and above)
Solar	740 GW_e	SW U.S.: 2,300 kWh/m^2-year	<1 GW_e	>740 times current	3750 sq. miles (approx. footprint of White Sands Missile Range, NM)
Nuclear	216 GW_e	n/a	98 GW_e	3.2	200 dedicated plants (1-1.2 GW_e)
THERMO-CHEMICAL					
Nuclear	300 GW_{th}	n/a	0 GW	n/a	125 dedicated plants (2.4 GW_{th})

a Examples of domestic resources that could be used to produce the 40 million short tons of hydrogen needed to fuel 150 million vehicles (values shown are based on that resource being used to produce the full 40 million tons of hydrogen); assumes a 2.2x improvement in efficiency over 27.5 mpg baseline fuel economy using hydrogen fueled vehicles. (Note: all table measurements are in short tons.)

b Calculations were made for the exclusive production of the amount of hydrogen requested. However, these systems can be configured to capture heat and generate both heat and electricity in combined heat and power (CHP) systems.

c Includes only that biomass not currently used for food, feed and fiber products.

d Other renewable power generation technologies can also serve as a resource for water electrolysis. For example, geothermal could provide 11 million tons of hydrogen per year (up to 68 million tons of hydrogen if estimates of undiscovered accessible resources are considered). Undeveloped hydropower resources and upgrades to existing hydroelectric plants could supply an additional 15 million tons of hydrogen per year.

Sources: *U.S. DOE, Energy Information Administration, Annual Energy Outlook 2002.*

Arthur D. Little (2001). "Aggressive Growth in the Use of Bio-derived Energy and Products in the United States by 2010."

D. Gray and G. Tomlinson (2002). "Hydrogen from Coal." Mitretek Technical Paper. MTR2002-31.

strategy is to produce hydrogen from an array of diverse feedstocks. This analysis is only ... million short tons of industrial hydrogen are produced annually and 150 million vehicles ... Note - The DOE Hydrogen Program is developing advanced technologies that could reduce resource consumption and/or the footprint of these resources.

Resource	Needed for H2 Economy[a]	Availability	Current Consumption	Current vs. H2 Economy Production (Factor, note b)
Reforming and/or Partial Oxidation				
Natural Gas	95 million tons/year	28 billion tons (technically recoverable as of 1/2000)	476 million tons/year	1.2
Biomass	400-800 million tons/year	800 million tons/year of biomass residue and waste, plus 300 million tons/year of dedicated crops[c]	200 million tons/year (3 quads for heat, power & electricity)	2-4
Coal	310 million tons/year	126 billion tons (recoverable bituminous coal)	1100 million tons/year (all grades)	1.3
Water Electrolysis[d]				
Wind	555 GW_e	3250 GW_e	4 GW_e	140
Solar	740 GW_e	SW U.S.: 2,300 kWh/m^2-year	<1 GW_e	>740 times current
Nuclear	216 GW_e	n/a	98 GW_e	2.2
Thermo-Chemical				
Nuclear	300 GW_t	n/a	0 GW	n/a

a. Examples of domestic resources that could be used to produce the 40 million short tons of hydrogen needed in the ... based on that resource being used to produce the full 40 million tons of hydrogen; assumes a 2.5x improvement in ... economy using hydrogen fueled vehicles. (Note: all table measurements are in short tons.)

b. Calculations were made for the exclusive production of the amount of hydrogen required. However, these systems ... generate both heat and electricity in combined heat and power (CHP) systems.

c. Includes only that biomass not currently used for food, feed and fiber products.

d. Other renewable power generation technologies can also serve as a resource for water electrolysis. For example, ... hydrogen per year (up to 58 million tons of hydrogen if utilization of undeveloped hydroelectric resources are considered), and upgrades to existing hydroelectric plants could supply an additional 1.5 million tons of hydrogen per year.

Sources: U.S. DOE, Energy Information Administration, Annual Energy Outlook 2002.

Arthur D. Little (2001). "Aggressive Growth in the Use of Bio-derived Energy and Products ...

D. Gray and G. Tomlinson (2002). "Hydrogen from Coal." Mitretek Technical Paper ...

6. Next Steps

- ✦ Coordinate the detailed multi-year RD&D plans and priorities for hydrogen and related technology development efforts in the Department to make them consistent with this planning document and the National Academies' study requested by DOE.

- ✦ To strengthen coordination within DOE, establish a working group composed of representatives from the Offices of Energy Efficiency and Renewable Energy; Fossil Energy; Nuclear Energy, Science and Technology; Science; Management, Budget, Evaluation/CFO; and Policy and International Affairs (in an oversight capacity). This working group should meet periodically to perform the following functions:
  - Evaluate the Department's progress in meeting milestones and performance goals in hydrogen and related activities.
  - Strengthen information exchange on technical developments.
  - Help ensure continued close integration among the Department's hydrogen-related activities (e.g., budgeting, execution, evaluation, and reporting).
  - Provide suggestions for improving management and technical performance.
  - Collaborate on systems analysis to understand the economic, energy, and environmental impacts of alternative technology pathways.

- ✦ Prepare a Program Management and Operations Plan to provide further detail on the overall management and integration of the Department's Hydrogen Program, including reporting requirements, oversight/advisory roles and responsibilities, and baseline requirements, cost, and schedule.

- ✦ Reflect the importance of the following activities in the Department's out-year planning and budgeting:
  - Exploratory research in hydrogen storage, production, and fuel cell cost and durability.
  - Hydrogen delivery and development of infrastructure (these activities need to be closely coordinated with the Department of Transportation (DOT), which is responsible for efforts to ensure the safety of the hydrogen delivery system).
  - Economic and systems analyses for determining and mitigating investment risks associated with hydrogen infrastructure and related technologies (e.g., fuel cell systems engineering and manufacturing plants).

- ✦ Increase the energy industry participation in the initiative, in recognition of the industry's key role in energy production and delivery infrastructures. Greater energy and utility industry participation is vital to a successful transition to a hydrogen economy.

- ✦ Strengthen and continue existing interagency coordination efforts to ensure that Federal investments in hydrogen energy development are leveraged to the maximum extent. The following agencies are participating with the Department of Energy in the Hydrogen Interagency Research and Development Task Force to discuss national hydrogen and related activities: Departments of Defense, Commerce, Transportation, Agriculture, and State; Office of Management and Budget; Office of Science and Technology Policy; National Science Foundation; National Institutes of Standards and Technology; Environmental Protection Agency; and National Aeronautics and Space Administration.

- Strengthen international cooperation on hydrogen-related research, development, and demonstration programs and on the development of interoperable codes and standards through the International Partnership for the Hydrogen Economy.
- Be aware of the nation's regulatory framework of energy, economic, and environmental policies at the federal, state, and local levels, and work with the appropriate agencies to coordinate the timing of policy instruments and regulatory actions to allow technology to meet market requirements.

Appendices

Appendix A. Hydrogen Production Pathways

Table A-1 summarizes a multitude of hydrogen production and delivery options. The large number of options is one of the key advantages to hydrogen as an energy carrier.

TABLE A-1. SUMMARY OF PRODUCTION OPTIONS

Raw Feedstock Options	Typical Processed Feedstock	Production Process Options	Process Energy Source Options	Production Strategy Options	Delivery Options
Fossil Fuels ♦ Coal ♦ Natural gas ♦ Oil	♦ Syngas ♦ Gasoline ♦ Diesel fuel ♦ Methanol ♦ Ammonia ♦ Direct use of raw stock	Thermal ♦ Reforming - Steam reforming - Partial oxidation ♦ Gasification ♦ Pyrolysis	Thermal ♦ Fossil ♦ Renewable ♦ Nuclear Electricity ♦ Fossil ♦ Renewable ♦ Nuclear	Distributed ♦ Fueling stations ♦ Individual buildings ♦ On-board	Hydrogen ♦ Gas pipeline ♦ Gas – rail or barge ♦ Gas – trucked ♦ Gas tube trailors ♦ Liquid – trucked ♦ Liquid – rail or barge ♦ Hydrides ♦ Other (e.g., carbon nanotubes)
Biomass ♦ Lignocellulose ♦ Starch ♦ Vegetable oils ♦ Black liquor	♦ Ethanol ♦ Methanol ♦ Biodiesel ♦ Biogas ♦ Sugars ♦ Direct use of raw stock	Electrochemical ♦ Electrolysis ♦ Photoelectro-chemical	Photolytic ♦ Solar	Semi-Distributed ♦ Market-Centered Central ♦ Resource-Centered	
Waste Material ♦ Municipal solid waste ♦ Stack gases ♦ Waste water	♦ Direct use of raw stock	Biological ♦ Photo-biological ♦ Aerobic fermentation ♦ Anaerobic fermentation			Other Gaseous Carriers ♦ Natural gas ♦ Ammonia
Water	♦ Direct use of raw stock				Liquid Carriers ♦ Ethanol ♦ Methanol ♦ Other organic liquids

The National Energy Policy calls for a diversity of domestic energy sources for national security and increased supply capability for our energy needs. Hydrogen can be produced from a variety of feedstocks including fossil fuels, nuclear, and renewable energy sources.

There are numerous hydrogen production processing options that can each be used for several of the feedstock options. Hydrogen can be produced in large central facilities and distributed to the point of use. It can be produced in a semi-distributed fashion near the larger market centers such as urban centers and urban corridors, or it can be produced directly at the point of use such as existing transportation refueling stations or even in a home or commercial building. It can be produced from hydrogen-rich liquid fuels in on-board reformers. It can be produced in a Vision 21 energy complex such as at an

Integrated Gasification Combined Cycle coal plant that could provide power, hydrogen, liquid fuels, and chemicals all at one site.

One can also envision a biorefinery using a biomass feedstock gasification operation (very similar to the coal energy complex example) based on wood residues, crop residues such as corn stover, or an energy crop such as switchgrass. Finally, hydrogen can be delivered from a central or semi-distributed production operation through a variety of means including new dedicated hydrogen pipelines, liquid transport via truck or rail, or possibly using new solid hydrides as a result of successful research.

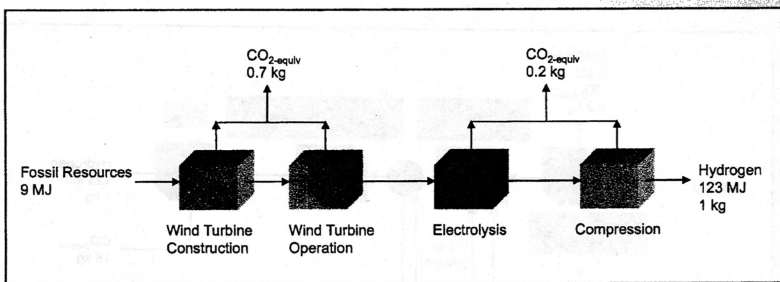
This variety of options for domestic feedstock, production, and delivery provides the diversity that the National Energy Policy requires. However, there are trade-offs within the matrix of options. Some options are better suited for central production, while others are better suited for distributed production. The cost and energy needed to distribute and deliver hydrogen is a major contributing factor because of its relatively low energy density. Further research and development will be needed to achieve competitive costs for hydrogen compared with conventional energy systems in use in the marketplace today; however, some options are closing in on cost goals.

Sufficient feedstock supply for hydrogen production is another area of concern. Table 1 (shown in Section 5, Program Benefits) summarizes recently compiled information on domestic resource availability. The table shows the resources that would be required from several key production routes to produce 40 million tons of hydrogen/year (enough to fuel 75% of the current light-duty vehicles on the road today, assuming fuel cells are used and are twice as efficient as today's conventional internal combustion engines running on gasoline). The calculations for most of the production routes shown in the table are based on current commercial or demonstrated technologies. Advanced production technologies are being developed within the DOE Hydrogen Program that could improve process efficiencies, resulting in reduced resource needs.

In the end, it is highly likely that hydrogen will be produced and delivered utilizing several feedstocks, processing options, and delivery options at a variety of scales ranging from large central production to very small local production. One of the tasks at hand is to develop a better understanding of the options available, the current and potential costs and energy efficiencies of these options, and the trade-offs each represent. From this understanding, we will further and continuously refine the DOE research and development plan for hydrogen production and delivery to ensure viable, cost-effective options become available for both the short term and long term.

Figures A-1 to A-4 present resource flows, fossil-fuel consumption, and greenhouse gas emissions for several potential hydrogen production pathways. Continuing analysis will be conducted to revise, refine, and expand these preliminary calculations. For those pathways that involve centralized production, transportation and delivery add significantly to energy requirements and emissions of air pollutants and greenhouse gases. Since there is a large variety of methods and distances involved in distribution and transport, no attempt has been made to quantify this aspect. Also, it is important to note that the fossil-fuel consumption and resulting emissions shown are highly dependent on the technology and equipment selected. Several advanced technologies are being developed for some production routes that could result in a 10-20% increase in system efficiency and similar decreases in emissions.

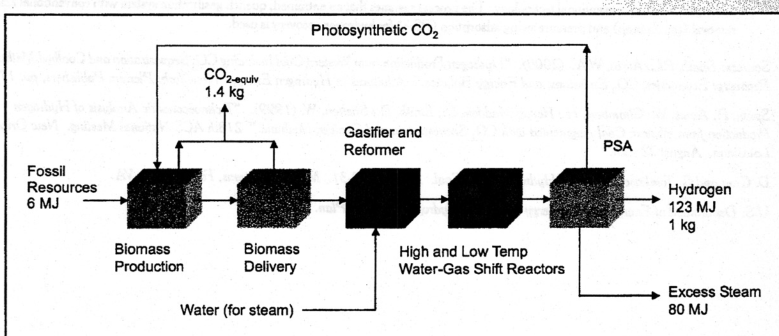
FIGURE A-1. DISTRIBUTED HYDROGEN PRODUCTION FROM WIND ELECTROLYSIS



Wind power is currently the most cost-effective renewable power technology. In conjunction with water electrolysis, wind can provide hydrogen at the consumer site with few emissions and with very low consumption of fossil resources. The CO_2-equivalent emissions from this process are associated with the manufacture and installation of the wind turbine (steel for construction and concrete for installation), and with the electricity needed to compress the hydrogen for on-site storage.

Source: Spath, P.L.; Mann, M.K. (2001). "Life Cycle Assessment - An Environmental Comparison of Hydrogen Production from Steam Methane Reforming versus Wind Electrolysis." The 12th National Hydrogen Association Meeting. March 6-8, Washington, D.C.

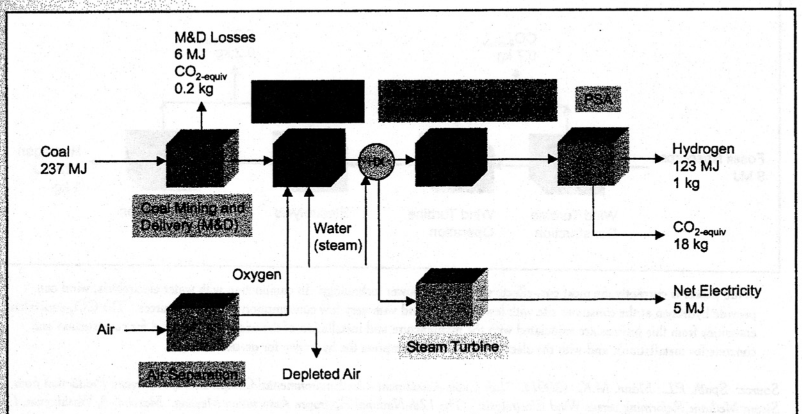
FIGURE A-2. HYDROGEN PRODUCTION FROM BIOMASS GASIFICATION.



Biomass-derived hydrogen is another low-CO_2 impact process for the production of hydrogen. Biomass (wood, agricultural residues, or energy crops) absorbs as much CO_2 from the atmosphere during growth as is released during gasification. Fossil resources are only needed for certain operations such as planting, cultivating, and collecting the biomass. In this diagram, we show the CO_2 being recycled by photosynthesis into additional biomass. It would also be possible to capture and sequester the CO_2 from the PSA unit (as discussed in the SMR case in Figure B-1) to derive additional benefits through a hydrogen process with significantly negative CO_2 emissions.

Source: Mann, M.K.; Spath, P.L. (1997). Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System. National Renewable Energy Laboratory, Golden, CO, TP-430-23076.

FIGURE A-3. ENERGY REQUIREMENTS AND GHG EMISSIONS – CENTRALIZED HYDROGEN PRODUCTION FROM COAL GASIFICATION



Based on bituminous coal

Domestic coal can be a major source of hydrogen in the near to mid-term. In the long-term, RD&D will improve technology that will lower the cost to produce hydrogen from coal, and also enable sequestration of carbon. Figure B-4 represents a process to produce hydrogen based on conventional technology. The process assumes that an entrained, quench gasification system with conventional acid removal (gas cleanup) and pressure swing adsorption (PSA) for hydrogen recovery is used.

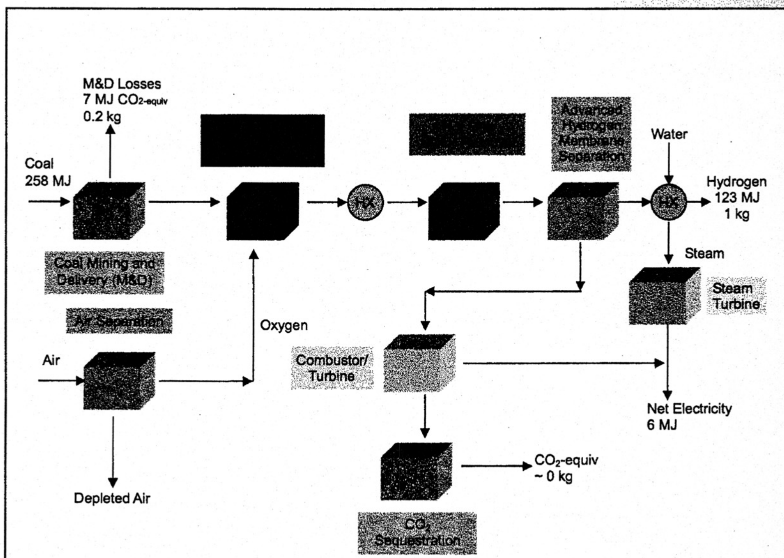
Sources: Spath, P.L.; Amos, W.A. (2000). "Hydrogen Production from Western Coal Including CO_2 Sequestration and Coalbed Methane Recovery: Economics, CO_2 Emissions, and Energy Balance." Advances in Hydrogen Energy. New York: Plenum Publishers, pp. 17-30.

Spath, P.; Amos, W.; Chambers, H.; Revay Madden, D.; Smith, D.; Shelton, W. (1999). "Technoeconomic Analysis of Hydrogen Production from Western Coal Augmented with CO_2 Sequestration and Coalbed Methane." 218th ACS National Meeting. New Orleans, Louisiana. August 22 - 26.

D. Gray and G. Tomlinson (2002). Hydrogen From Coal. MTR 2002-31. Mitretek Systems, Falls Church, VA.

U.S. Department of Energy, Fossil Energy Program: Hydrogen Program Plan.

FIGURE A-4. ENERGY REQUIREMENTS AND GHG EMISSIONS – CENTRALIZED HYDROGEN PRODUCTION FROM ADVANCED COAL GASIFICATION WITH SEQUESTRATION



Based on bituminous coal

This figure represents a process for hydrogen production from coal that uses advanced gasification technology, advanced membrane technology for hydrogen separation and carbon dioxide removal, and carbon sequestration. In this configuration, advanced two-stage gasification with hot gas cleanup is used in combination with a ceramic membrane system operating at nearly 600°C that is capable of shifting and separating hydrogen from clean synthesis gas. It is assumed that 90 percent of the synthesis gas is converted in this membrane system. The hydrogen produced is separated at low pressure and must be compressed. The remaining synthesis gas, containing mostly carbon dioxide with some carbon monoxide and hydrogen, is then combusted with oxygen in a gas turbine to provide power for the plant. Oxygen is used so that a concentrated stream of carbon dioxide is produced for sequestration. Heat is recovered from both the gas turbine exit gas and from the hot hydrogen in heat recovery steam generators (HRSGs) where the steam produced is sent to a steam turbine to provide additional power. The excess power produced is then sold. Even more advanced concepts are planned to be developed toward 2020 which would employ advanced solid oxide fuel cells in addition to the other technology advancements previously discussed. These hydrogen and electricity co-production plants could provide significant additional reductions in the cost of hydrogen.

Sources: D. Gray and G. Tomlinson (2002). Hydrogen From Coal. MTR 2002-31. Mitretek Systems, Falls Church, VA.

U.S. Department of Energy, Fossil Energy Program: Hydrogen Program Plan.

Appendix B. Glossary/Acronyms

AC .... Alternating Current
ANSI .... American National Standards Institute
ASME .... American Society of Mechanical Engineers
ATS .... Advanced Turbine Systems
CHP .... Combined Heat and Power
CO .... Carbon Monoxide
CO_2 .... Carbon Dioxide
CSA .... Canadian Standards Association
DC .... Direct Current
DOD .... U.S. Department of Defense
DOE .... U.S. Department of Energy
DOT .... U.S. Department of Transportation
EPA .... U.S. Environmental Protection Agency
FY .... Fiscal Year
ICC .... International Code Council
IEC............... Independent Electrical Contractors
IEEE .... Institute of Electrical and Electronic Engineers
ITM .... Ion Transport Membrane
Electrolyzer ... A device that uses electricity to produce hydrogen from water
EERE .... Energy Efficiency and Renewable Energy
FE .... Fossil Energy
GGE .... Gallon of Gasoline Equivalent
ISO .... International Standards Organization
kW................ Kilowatt
MMT .... Million Metric Tons
MMTCE...... Million Metric Tons Carbon Equivalent
NASA.......... National Aeronautics and Space Administration
NE .... Nuclear Energy
NIST............ National Institute of Standards and Technology
NO_x .... Nitrogen Oxides
NSF .... National Science Foundation
PEM .... Polymer Electrolyte Membrane
PSI .... Pounds per Square Inch
QC .... Quality Control
R&D .... Research and Development
RD&D .... Research, Development and Demonstration
RFP .... Request for Proposal
SAE .... Society of Automotive Engineers
SECA .... Solid State Energy Conversion Alliance
SMR .... Steam Methane Reformer
SOFC .... Solid Oxide Fuel Cell
SOX............. Sulfur Oxide
UL .... Underwriters Laboratories, Inc.
USDA.......... United States Department of Agriculture
V .... Volt
VOC .... Volatile Organic Compound

Appendix C. Contacts, Resources, and Weblinks

POSTURE PLAN TEAM: CORE MEMBERS

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DOCUMENT CITATIONS

A National Vision of America's Transition to a Hydrogen Economy: To 2030 and Beyond
February 2002
www.eere.energy.gov/hydrogenandfuelcells

National Hydrogen Energy Roadmap
November 2002
www.eere.doe.gov/hydrogenandfuelcells

Basic Research Needs for the Hydrogen Economy: Report on the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use
May 13-15, 2003
www.sc.doe.gov/bes/hydrogen.pdf

National Energy Policy
May 2002
www.whitehouse.gov/energy

Department of Energy FY2005 Budget Request
http://www.mbe.doe.gov/budget/05budget/index.htm

WEB SITES OF RELEVANT DOE OFFICES

Office of Energy Efficiency and Renewable Energy
www.eere.energy.gov

FreedomCAR and Vehicle Technologies Program
www.eere.energy.gov/vehicle.html

Hydrogen, Fuel Cells and Infrastructure Technologies Program
www.eere.energy.gov/hydrogenandfuelcells

Office of Fossil Energy
www.fe.doe.gov

Office of Nuclear Energy, Science, and Technology
www.ne.doe.gov

Office of Science
www.science.doe.gov

Solid State Energy Conversion Alliance
www.seca.doe.gov

APS PANEL ON PUBLIC AFFAIRS

March 2004

THE HYDROGEN INITIATIVE

Current technology is promising but not competitive. More emphasis needed on solving fundamental science problems.

Issue

President Bush has proposed a $1.2 billion Hydrogen Initiative that has a goal of developing a hydrogen-fueled car and supporting infrastructure by the year 2020.

Recommendations

Major scientific breakthroughs are required for the Hydrogen Initiative to succeed. Basic science must have greater emphasis both in planning and in the research program. The Hydrogen Technical Advisory Committee should include members who are deeply familiar with the core basic science problems. "Bridge" technologies should be given greater attention. And, the Hydrogen Initiative should not displace research into promising energy efficiency and renewable energy areas.

Detailed Recommendations: p11, 14

The APS

The American Physical Society is the nation's primary organization of research physicists with 43,000 members in industry, universities, and national laboratories.

APS Discussion Paper

The APS occasionally produces discussion papers on topics currently debated in Congress in order to inform the debate with the perspectives of physicists working in the relevant issue areas. The papers are overseen by the APS Panel on Public Affairs but have not been endorsed by the APS Council.

Executive Summary

In 2003, President Bush announced a multi-year $1.2 billion Hydrogen Initiative intended to reduce the nation's dependence on foreign oil through the production of hydrogen fuel and a hydrogen-fueled car. The Initiative has envisioned the competitive use of hydrogen in commercial transportation by the year 2020.

Currently, the US hydrogen industry produces 9,000,000 tons of hydrogen per year. Several hydrogen-fueling stations are scheduled to open this year. And, several models of hydrogen-fueled cars have been demonstrated.

However, none of the current technologies are competitive options for the consumer. The most promising hydrogen-engine technologies require factors of 10 to 100 improvements in cost or performance in order to be competitive. Further, hydrogen cannot simply be extracted from the air, ground or water – it must be produced. Yet, as the Secretary of Energy has stated, current hydrogen production methods are four times more expensive than gasoline. Finally, no material exists to construct a hydrogen fuel tank that meets the consumer benchmarks. A new material must be developed.

These are enormous performance gaps. Incremental improvements to existing technologies are not sufficient to close all the gaps. For the Hydrogen Initiative to succeed, major scientific breakthroughs are needed.

Basic science must have greater emphasis both in planning and in the research program. The Hydrogen Technical Advisory Committee should include members of the basic research community who are familiar with the relevant science problems. Further, given the multidisciplinary nature of the scientific problems involved, principal-investigator funded research should be complemented with the creation of several peer-reviewed, competitively bid, Research Centers that focus on the relevant research problems in hydrogen production, storage and use.

In the event that the timeline for hydrogen vehicles slips beyond 2020, there will be greater need for technologies that serve as a so-called "bridge" between the current fossil-fuel economy and any future hydrogen economy. Increasing the focus on basic science and engineering that advances such technologies would serve as a sensible hedge and at the same time maintain the development of technologies that show clear short-term promise. Similarly, the Hydrogen Initiative must not displace research into promising energy efficiency and renewable energy areas.

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Contents

I. Introduction

Technology commercialization projects all face a critical decision point in their development. The capability of the technology must be evaluated, based on the current state of the relevant science, to determine whether the project is ready to proceed aggressively to demonstrations. The Government has faced such decision points before in large-scale commercialization programs.

In his State of the Union Address, the President of the United States proposed an energy-technology program intended to generate the economical production of an alternative fuel that could revolutionize the transportation sector. A diverse group of companies, universities, and national labs would work together. The new fuel would substitute for oil imports and make our country energy independent.

That was 1975: Gerald Ford proposed an initiative for coal-based Synthetic Fuels in his State of the Union Address.[1]

In 2003, President Bush announced a $1.2 billion Hydrogen Initiative intended to generate the economical production of hydrogen fuel as well as a hydrogen car and supporting infrastructure.[2] Like the Synfuel program, the Hydrogen Initiative brings together a diverse group of companies, universities and national labs with an overarching goal of developing a substitute for oil and making our country more energy independent.

Since the Synfuel program goals - and its $2 billion cost - are similar to the Hydrogen Initiative, it is valuable to briefly consider its history.

The falling price of oil in the 80s led to a suspension of industrial support for the Synfuel program and undermined the prospects for commercial application. And, relevant to the Hydrogen Initiative, the Synfuels program had rushed into demonstration projects that were not backed by realistic assessments of the state of technology. As the demonstrations ran into trouble, the program missed an opportunity to advance the state of knowledge and further the long-term commercial prospects of energy production based on clean coal technology. By 1983, the program had lost support in Congress.

In general, the allocation of resources between demonstration projects and relevant basic science must be based on the current commercial readiness of the technology to compete in the market place or to meet national security objectives.

Budgets should be based upon the commercial readiness of the technology.

Demonstration projects play a critical role in a balanced commercialization project. For example, they can lead to cost reductions and accelerate the development of codes and standards. But they can also divert effort toward

[1] January 15, 1975, http://www.geocities.com/americanpresidencynet/1975.htm
[2] January 26, 2003, http://www.geocities.com/americanpresidencynet/2003.htm

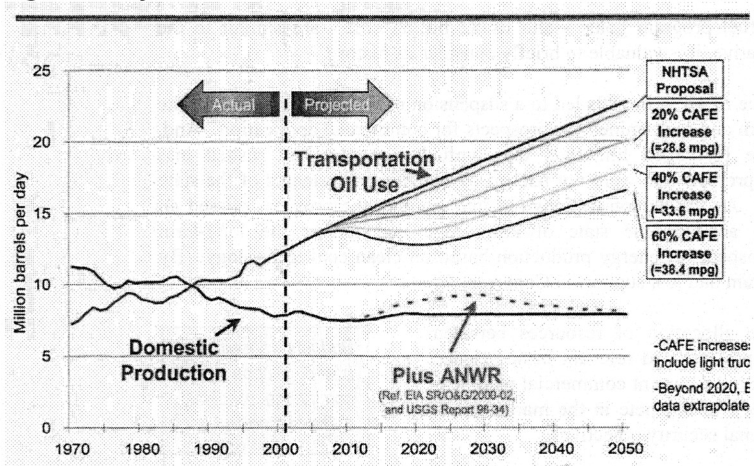
technology with limited potential. So, while demonstrations are an essential part of a government commercialization program, they will only benefit the overall program when a sufficient knowledge base exists.

For the Hydrogen Initiative to be successful, it must give more emphasis to achieving significant advancements in the knowledge base. With such balanced technological development and appropriate long-term perspective, hydrogen has the potential to be economically produced in the future from renewable sources as well as a variety of fossil fuel, including the vast reserves of domestic coal.

If major scientific challenges to storage and use can be overcome, hydrogen fuel also has the potential for addressing the Administration's goal of enhancing energy security by reducing dependence on imported oil. Further, depending on the manner in which the hydrogen fuel is produced, hydrogen fuel can significantly reduce atmospheric release of carbon dioxide.

The Hydrogen Initiative is shaped by the recognition that current US energy dependence is heavily determined by the transportation sector. Transportation accounts for two-thirds of the 20 million barrels of oil the nation uses every day.[3] In order to enhance our energy security, a substitute for oil should be pursued, since neither increasing fuel efficiency nor additional drilling offers a long-term solution to closing the gap between domestic production and oil use (Fig 1).[4]

Figure 1. Projected U.S. Oil Use and Domestic Production



[3] US Department of Energy, http://www.sae.org/calendar/pfs/key_chalk.pdf, p 5.
[4] US Department of Energy, http://www.ccities.doe.gov/conference/palm/pdfs/gross_pathway.pdf, p 4.
This DOE figure is speculative and is based on several long-term projections. It estimates US domestic oil production flat to 2050 at about 2.9 billion barrels per year. However, US production has fallen from a peak in 1970 of roughly 3.5 billion barrels/year to roughly 2.1 billion barrels/year in 2000 (down 40%). Further, the demand lines are based upon long-term projections of economic growth and population increase.

The Initiative has set a goal for "the commercial use of fuels cells in transportation, portable power, and stationary and distributed power applications by 2012."[5] In particular, the Initiative envisions the competitive use of hydrogen in commercial transportation by the year 2020. These 2012 and 2020 goals pose significant challenges. The fundamental problem is that a large performance gap exists between the current state of the technology and the final goals.[6,7,8,9]

Current hydrogen technologies are not a competitive choice for the consumer.

None of the existing technologies are a competitive choice for the consumer. The most promising hydrogen-engine technologies require factors of 10 to 100 improvements in cost or performance in order to be competitive. Current production methods are four times more expensive than gasoline. And, no material exists to construct a hydrogen fuel tank that meets the consumer benchmarks. A new material must be developed.

Given these enormous performance gaps, the strategy of devoting too large a share of the program to demonstrations of the automotive application is problematic. To insure the ultimate success of the Hydrogen Initiative, indeed for any new technology, it is critical that resources are properly allocated between demonstration projects and research & development.

The program needs substantially greater emphasis on solving the fundamental science problems. Section 2 of this report examines this issue and makes recommendations to increase the possibility of achieving the 2020 goal of commercial hydrogen transportation.

Because of the large performance gaps, it is possible that the 2020 timeline for hydrogen vehicles may slip. Therefore, it is prudent to maintain strong research programs into technologies that serve as bridges between the current fossil-fuel economy and any future hydrogen economy. Further, technologies that are important complements to the goals of a hydrogen economy should not have their budgets pressed as greater emphasis is placed on the Hydrogen Initiative. Section 3 of this report examines these issues and makes recommendations to insure that important opportunities to advance the state of knowledge and further our nation's energy security are still maintained while prudently undertaking the Hydrogen Initiative.

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[5] National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf, p 3.
[6] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003), http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE
[7] "Basic Research Needs to Assure a Secure Energy Future," (Feb. 2003), http://www.sc.doe.gov/bes/besac/Basic_Research_Needs_To_Assure_A_Secure_Energy_Future_FEB2003.pdf
[8] Programmatic Publications, DOE Energy Efficiency and Renewable Energy, Hydrogen Fuel Cell Infrastructure Technology Program, http://www.eere.energy.gov/hydrogenandfuelcells/pubs.html#roadmaps
[9] "Basic Research Needs for the Hydrogen Economy," a report from the Basic Energy Sciences Workshop (May 2003), http://www.sc.doe.gov/bes/hydrogen.pdf

II. Knowledge Gaps & Key Science Areas

> *The Hydrogen car faces challenging expectations from the consumer.*

More than 95 years of scientific and engineering expertise has been directed at the development of the automobile and its corresponding infrastructure of 125,000 domestic gas stations and worldwide network of oil wells, refineries, and delivery systems. A result of that century-long process has been the creation of a demanding set of consumer expectations. The Hydrogen Initiative envisions developing a new fuel, a new car, and a corresponding infrastructure that can meet consumer expectations within 12 years. This poses a significant challenge to the scientific and engineering community.

There are enormous performance gaps between the current state of hydrogen technology and what is required to achieve a commercially viable hydrogen transportation sector. The scientific challenges exist in the all three of the primary areas of the Hydrogen Initiative: production, storage, and use.

To illustrate the challenges, Figure 2 lists just a few of the performance goals established in the FreedomCar Partnership Plan.[10] The table compares these goals to estimates of the current state-of-the-art in a number of possible technologies. However, the challenges are even greater than the chart indicates: each technology component must achieve several performance goals at once. Many technologies may excel in one area but have poor performance in another. Furthermore, the performance goals in each of these stages - production, storage, use - must be met *simultaneously* before the hydrogen economy will be viable. Thus, the magnitude of the problem is even greater than any one given challenge.

The next three subsections examine in detail the specific research challenges faced in the areas of production, storage, and use. There are some common threads to the research challenges posed by each. All would benefit from research into more effective catalysts - chemicals that speed up certain reactions - and membranes - films that pass one compound while blocking others. Most of these steps require the development of new materials that effectively store hydrogen, operate at high temperatures, and withstand corrosion.

Production

Hydrogen does not exist in accessible quantities on Earth. It cannot simply be extracted from the air, ground or water. Instead, hydrogen must be produced. Consequently, an energy source is required in order to create the hydrogen fuel envisioned in the Hydrogen Initiative.[11]

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[10] http://www.eere.energy.gov/vehiclesandfuels/pdfs/program/freedomcar_partnership_plan.pdf. The table is not an exhaustive list of performance targets, but an illustrative one. Goals not shown include, for example, standards for the flow rate of hydrogen through a tank and the number of fill and empty cycles it must tolerate. The table also identifies only a sampling of the key challenges.

[11] National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf

Figure 2. Benchmarks, Knowledge Gaps, and Key Science Areas

Consumer Benchmark[12]	Hydrogen Technology	Minimum factor of Improvement to be Competitive[13]	Challenges	Key Science Areas
Production: $1.50 per gallon	Natural Gas Reforming Coal Gasification Electrolysis	4 to10	Cost Sequestration of Carbon Dioxide Electrolysis Efficiency	Membranes, Catalysts, Renewable Energy, Bio-Engineering, Sequestration, Electrodes
Storage: 300 miles on a tank, 3 to 5 minutes to fill	Compressed Gas Storage Liquid Storage Solid Storage	2 to 3	Leaks, Embrittlement Energy cost, Evaporation Release of fuel at expected temperatures and pressures	Material Science: a new storage material must be developed
Use: 100,000 miles or 5 year warranty, engine cost roughly $2,000- $5,000	Fuel Cell	10 to 100	Impurities, Durability, Materials cost	Material Science, Membranes, Catalysts, Combinatorial Chemistry

Strategically, the long-term goal of the Hydrogen Initiative is to develop an *efficient*, *economical* and *clean* means of producing hydrogen.[14] To be efficient, the production process should not use excessively more energy to create hydrogen fuel than is derived from burning hydrogen fuel. To be economical, hydrogen fuel should not cost more than current fuels. And, for the fuel to be clean, more

[12] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003), http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE; National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf, p 19; "Cost and Efficiency of Automobile Engine Plants," Daniel E. Whitney, et. al., (August, 2001), http://web.mit.edu/ctpid/www/Whitney/morepapers/Engine.pdf

[13] Production costs for coal gasification are calculated to become competitive once proposed plants begin operating at full capacity, http://www.nap.edu/books/0309091632/html/, 5-7; Office of Fossil Energy, http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml; Spencer Abraham, http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE; "Basic Research Needs for the Hydrogen Economy," http://www.sc.doe.gov/bes/hydrogen.pdf.

[14] National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf

carbon-dioxide (CO_2) and toxins cannot be released in creating and using hydrogen fuel than would have been emitted in burning current fuels.

The United States hydrogen industry currently produces nine million tons of hydrogen per year for a variety of non-transportation uses. The primary means of production is the extraction of hydrogen from natural gas through a process known as "steam reforming". However, steam reforming is operating near theoretical limits and is still several times more expensive than gasoline.[15] Further, making it a clean production method would add significantly to the cost.

There is no currently available competitive and long-term means of *efficiently*, *economically* and *cleanly* producing hydrogen. At a minimum, as Secretary of Energy Spencer Abraham has stated, costs must be cut by a factor of four.[16]

A likely near-term option to economically produce hydrogen is coal gasification. The technology is relatively mature, and costs are calculated to become competitive once proposed plants begin operating at full capacity.[17] Yet, there are still technical issues to address. The hydrogen produced by this method contains contaminants and the fuel must be purified before using it in hydrogen fuel-cell engines. To effectively purify the hydrogen, researchers must develop catalysts that resist poisoning by the contaminants in the coal.[18] Furthermore, materials must be discovered that can withstand high temperatures and corrosion.

Coal gasification can release significant quantities of CO_2. Thus, to create clean hydrogen it is critical to develop technology that will capture and store - or sequester - the CO_2. The $1 billion FutureGen program is directing resources at this problem.[19] Since the sequestration problem is a significant scientific challenge with applications that extend beyond the hydrogen initiative, FutureGen should carefully balance Hydrogen Initiative goals and timelines with the opportunity to significantly advance the knowledge base on the relevant science of sequestration.

Hydrogen can also be produced by using electricity to separate hydrogen out of water. This process, called electrolysis, can be made to work using any source of electricity including hydropower, wind, solar, and nuclear fission. However, electrolysis is at best only 75% efficient. The current cost to produce hydrogen in this manner is primarily driven by the cost of electricity and is roughly 4 to 10 times more expensive than gasoline. One of the major research challenges is to develop a more effective catalyst to facilitate the electrolysis process.

Renewable energy research is a direct benefit to the goals of the Hydrogen Initiative.

[15] Department of Energy, http://fossil.energy.gov/programs/fuels/hydrogen/hydrogen-from-gas.shtml
[16] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003), http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE
[17] "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs," National Research Council, February 2004, http://www.nap.edu/books/0309091632/html/
[18] "Basic Research Needs for the Hydrogen Economy," (May 2003), http://www.sc.doe.gov/bes/hydrogen.pdf
[19] http://www.fossil.energy.gov/programs/powersystems/futuregen/futuregen_factsheet.pdf

The cost of electrolysis-production improves directly as power sources - such as wind, solar, and nuclear - become cheaper and more efficient. Therefore, a continued investment in renewable energy is a direct benefit to the overall goals of the Hydrogen Initiative. The $1.1 billion Next Generation Nuclear Plant (NGNP) is intended to demonstrate, among other things, commercial-scale hydrogen production by 2015.[20] Since nuclear power is a critical future energy option, Hydrogen Initiative goals and timetables for NGNP should be carefully balanced with the opportunity to significantly advance nuclear power.

Researchers are also exploring novel but promising production methods. For example, in a process known as photolysis, certain algae produce hydrogen by directly splitting water.[21] These biological systems do not require the expensive metal catalysts that are currently used to produce hydrogen. While this research may not contribute in time for the 2020 goal for commercial hydrogen vehicles, it may stimulate ideas for producing a new low cost catalyst. It has the potential to make a long-term contribution, but science advances are required to make it commercially viable.

Storage

Safely and efficiently storing hydrogen in a car's fuel tank are enormous challenges to achieving the hydrogen economy.[22] Indeed, no material exists today that can be used to construct a hydrogen fuel tank that can meet the consumer benchmarks.[23] A new material must be developed.

Hydrogen storage is the primary scientific challenge… A new material must be developed.

As evident in Figure 2, current hydrogen storage technologies are unable by factors of two or more to meet the consumer benchmarks. The requirement that a vehicle be able to travel 300 miles between refueling is a significant challenge for hydrogen storage. Hydrogen is a diffuse gas and the challenge is to store a sufficient amount of it in a tank. To meet consumer expectations, the tank must be capable of being refueled within 3-5 minutes and it must withstand hundreds of refuelings over a 15-year lifetime.

Current hydrogen systems include pressurized tank storage (for gaseous or liquid hydrogen) and "solid-state storage" (in which hydrogen molecules are either absorbed onto or chemically bound up in the storage medium).

High-pressure, lightweight tanks of adequate strength have been made of carbon-fiber-reinforced materials. But, even at the extremely high pressures attainable by this technology, the energy that can be stored in this type of tank is many times less than a comparable tank of gasoline. Another drawback is that a significant amount of energy must be expended to compress the hydrogen into the tank. The

[20] http://www.nuclear.gov/infosheets/hydrogenfactmarch2003.pdf
[21] "Basic Research Needs for the Hydrogen Economy," http://www.sc.doe.gov/bes/hydrogen.pdf
[22] "Fuel Cell Vehicles: Race to a New Automotive Future"
http://www.technology.gov/reports/TechPolicy/CD117a-030129.pdf
[23] Jan. 2003, Office of Technology Policy report, *Fuel Cell Vehicles: Race to a New Automotive Future.* [OTP]

over-arching research need is for new materials that are strong, reliable, and low cost.

A tank can hold more hydrogen liquid than hydrogen gas, so long as the liquid is kept extremely cold (-450 Fahrenheit). Still, the energy content is roughly a factor of two below the consumer benchmarks. Several automobile manufacturers are conducting research on liquid storage.[24] But, the challenges include a large energy requirement to liquefy the hydrogen and the loss of hydrogen through evaporation. Research needs include strong, durable and leak-proof materials.

Currently, the most promising technology is "solid-state storage" in which hydrogen molecules are embedded in a material. But finding just the right materials in which to embed hydrogen involves tradeoffs between materials that bind hydrogen tightly enough to store it and materials that readily release hydrogen for use at reasonable temperatures and pressures. To date, the storage of hydrogen by this method is a factor of 3 below the benchmarks.

Use

The basic concept of the hydrogen engine has been known since the invention of the "fuel cell" in 1839 by Sir William Grove. In the 1950s, NASA turned the concept into a practical device to produce power for space vehicles. However, as evident from Figure 2, there are significant barriers to developing an economically competitive hydrogen engine.

In a fuel cell, hydrogen is injected at one terminal and oxygen is injected at another terminal. Between these terminals is an electrolyte, or membrane. The hydrogen is split into two protons and two electrons. The electrons flow through an electric motor that turns the wheels of the car, while the protons flow through the electrolyte to the other terminal and combine with oxygen to generate water.

In order to be competitive, fuel cells require significant advances in catalysis and membrane research. Cost-competitive fuel cells require membranes with: very high permeability and selectivity in gas separations; high conductivity; and, durability at high temperatures and in corrosive operating environments. Meeting these three needs calls for an intensive effort in materials synthesis, characterization, and modeling of specially designed materials including: nanostructures, inorganic films, diffusion membranes, and low-cost, high-conductivity proton conductors.

Since catalytic performance is a key factor for many essential elements of the hydrogen economy (including fuel cell efficiency, storage, and production), there is a critical need for breakthrough research into catalysts.[25] Clearly it is desirable to reduce or eliminate platinum in the fuel cell since this is the primary driver of

[24] Jerald A. Cole, "Overview of the hydrogen-powered economy – today and beyond," California Hydrogen Business Council, presentation to Association of Energy Engineers, Southern California Chapter, 14 March 2002, http://www.ch2bc.org.

[25] Typical publications include: E. Katz *et al.*, "A biofuel cell with electrochemically switchable and tunable output," *J. Am. Chem. Soc.* *125*, 6803 (2003); I.V. Mishakov *et al.*, "Nanocrystalline MgO as a dehydrohalogenation catalyst," *Journal of Catalyi 286*, 40 (2002).

the cost. Several cutting-edge research concepts have the potential to address the problem. Using combinatorial chemistry, different combinations of atoms or molecules can be rapidly "produced" by computer and screened for desired properties. When promising trends are revealed, they can be followed up with detailed laboratory work. This technique has already identified a material, which might be up to 40 times more effective as a catalyst than platinum.[26]

The Hydrogen Initiative has an aggressive schedule for fuel-cell demonstration projects.[27] Given the need for significant breakthroughs in membranes and catalysts to make fuel cells commercially competitive, these demonstration goals must be carefully balanced with opportunities to advance the knowledge base.

Hydrogen Initiative Emphasis

There is an enormous gap between our present capabilities for hydrogen production, storage, and use and those required for a competitive hydrogen economy. As detailed in a Department of Energy workshop report, simple incremental advances in the present state of the art cannot close this gap.[28] The only possibility for narrowing the gap significantly is a program of high-risk/high-payoff basic science that is coupled to applied programs. The objective must not be evolutionary advances but revolutionary breakthroughs in understanding.

Figure 3. Hydrogen Initiative Budget in thousands

	FY '04 Request	FY '04 Final	FY '05 Request
Energy Efficiency & Renewable Energy (Dept of Energy)	$165,482	$147,178	$172,825
Fossil Energy (Dept of Energy)	$11,555	$4,889	$16,000
Nuclear Energy (Dept of Energy)	$4,000	$6,377	$9,000
Dept of Transportation	$674	$555	$832
National Science Foundation	$0.0*	$0.0*	$0.0
Basic Energy Sciences (Office of Science, Dept of Energy)	$0.0*	$0.0*	$29,183
Total	$181,711	$158,999	$227,840

* An additional $7.7 million at the Office of Science and $10.3 million at the NSF were identified as on-going research that contributes to the goals of the Hydrogen Initiative.

Given the large performance gaps, basic science is critical to the ultimate success of the Hydrogen Initiative. Yet, basic science is not receiving appropriate

[26] P. Strasser *et al.*, "High throughput experimental and theoretical predictive screening of materials-a comparative study of search strategies for new fuel cell anode catalysts," *J. Phys. Chem. B* ***107***, 11013 (2003).
[27] DOE plans to demonstrate commercial readiness of fuel cells starting in 2009, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/asilomar2003.pdf, p 7.
[28] "Basic Research Needs for the Hydrogen Economy," (May 2003), http://www.sc.doe.gov/bes/hydrogen.pdf

emphasis in the program. As the budget breakdown in Figure 3 shows, in FY'04, the nation's primary basic science agencies - the National Science Foundation and the Office of Science at the Department of Energy – did not receive support from the Hydrogen Initiative.

In addition, earmarks skewed key funding priorities in FY '04. For example, the solicitation "Grand Challenge For Basic And Applied Research In Hydrogen Storage" was intended to fund competitively bid proposals addressing the key issue of hydrogen storage. While $30 million was requested for this funding, as the budget moved through Congress, $28 million was earmarked. In total, roughly $42 million of the FY '04 Hydrogen Initiative was earmarked.

The FY'05 request includes $29 million for basic research in the Office of Science. This is a dramatic improvement over FY'04 budgeting and demonstrates a growing recognition that the Hydrogen Initiative cannot succeed until several relevant science problems are solved.

However, the budget directed toward basic research at NSF and Office of Science, still does not reflect adequate appreciation that the large performance gaps can only be reduced by major scientific breakthroughs. Indeed, the budget emphasizes demonstration projects over basic science. Yet, given the enormous challenges facing hydrogen storage, for example, investments in storage demonstrations would be highly premature and there may be little urgency for demonstrations in some other areas at this time.

For the Hydrogen Initiative to be successful, basic science must have greater emphasis both in planning and in the research program.

Basic research should be represented in key planning activities of the Hydrogen Initiative. The White House Office of Science and Technology Policy has included members of NSF and members of Basic Energy Sciences within DOE in its cross-cutting planning. This should be extended. Representatives of BES should participate in the Hydrogen Policy Group within DOE. And, the newly forming Hydrogen Technical Advisory Committee should include members of the basic research community who are familiar with the key science problems.

The Hydrogen Initiative must give greater emphasis to achieving significant advancements in the knowledge base. Demonstration projects can play a critical role in a balanced commercialization project by achieving cost reductions and accelerating the development of codes and standards. But they can also divert effort toward technology with limited potential. So, while demonstrations are an essential part of a government commercialization program, they only benefit the overall program when a sufficient knowledge base exists.

Demonstrations only benefit the program when an adequate knowledge-base exists.

The Hydrogen Initiative must place greater emphasis on solving the relevant research problems in production, storage and use. The programs to be funded should be selected by a competitive peer-reviewed process. Much of the basic and applied research will cut across conventional academic disciplines, with strong linkages between experimental and theoretical explorations. Some of the knowledge gaps can be addressed by incremental progress in well-established research areas while others will require coupled breakthroughs in the physical sciences, biological sciences, and engineering.

Many of the individual knowledge gaps themselves need multidisciplinary teams to make progress. This may be achieved by complementing principal investigator research with multidisciplinary research centers - as is beginning to occur in Initiative planning and as some Members of Congress are urging.

Since the goal of a competitive hydrogen-transportation sector involves both shorter and longer-term components, it would be desirable to connect the multidisciplinary research centers to related efforts in industry and in DOE laboratories. This could be achieved by exchange of personnel and through coordinated efforts housed in industry and in DOE laboratories.

Earmarking funds will not produce the desired, competitive result. Research centers established by federal initiatives that are considered both successful and exemplary have relied on competition and peer review.[29] Key to their success are: an initial competition for funds, with a strong peer review component in the evaluation of proposals; fixed terms for federal support (five years is customary), with reauthorization contingent on a second, comprehensive review; and a fixed total term for federal support (one reauthorization, or a total of ten years, has generally been adequate to accomplish the initial goals and to position the Center, if successful, to continue with private or philanthropic financial sources).[30]

Recommendations:

- Basic science must have greater emphasis in key planning activities for the Hydrogen Initiative. The Hydrogen Technical Advisory Committee should include members of the basic research community who are familiar with the key science problems.

- Basic science should have greater emphasis in the research program for the Hydrogen Initiative. Principal-Investigator research should be increased. And, PI research should be complemented with competitively-bid, peer-reviewed multidisciplinary research centers that carry out basic research in the key research areas of production, storage and use. These university-based centers should have active industry and national laboratory participation.

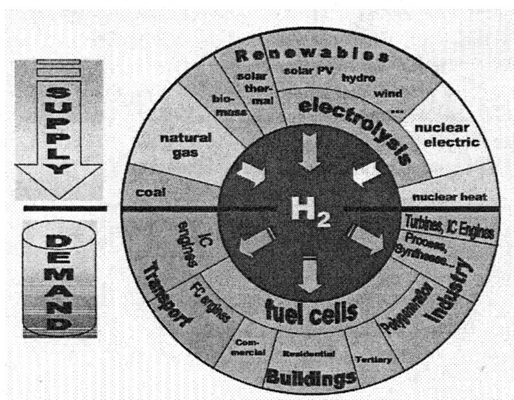
[29] For example, the University-Industry Initiative sponsored by National Science Foundation.
[30] Roger Noll, "Challenges to Research Universities," Brookings Institution (1998).

III. Bridge Technologies & Alternative Applications

The Hydrogen Initiative has envisioned "the commercial use of fuels cells in transportation, portable power, and stationary and distributed power applications by 2012."[31] In particular, the Initiative envisions the competitive use of hydrogen in commercial transportation by the year 2020. These goals pose a significant challenge. The problem is that a large gap exists between the current state of the technology and the final goals.[32]

These challenging timelines should be balanced with a recognition that the development of a Hydrogen Economy can benefit from investing in promising research in a variety of technology areas. Research into energy efficiency, renewable energy, bridge technologies, and hydrogen applications in non-transportation sectors are all investments that present an opportunity to advance the state of knowledge, further commercial prospects that enhance the nation's energy security, and reduce the atmospheric release of carbon dioxide.

Figure 4. Supply and Demand in a Hydrogen Economy [33]



The Federal support of renewable energy and energy efficiency research is appropriately recognized by both the Administration and Congress to be an

[31] National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf, p 3.

[32] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003), http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE; Programmatic Publications, DOE Energy Efficiency and Renewable Energy, Hydrogen Fuel Cell Infrastructure Technology Program, http://www.eere.energy.gov/hydrogenandfuelcells/pubs.html#roadmaps; "Basic Research Needs to Assure a Secure Energy Future," a report from the Basic Energy Sciences Advisory Committee (Feb. 2003); http://www.sc.doe.gov/bes/besac/Basic_Research_Needs_To_Assure_A_Secure_Energy_Future_FEB2003.pdf; "Basic Research Needs for the Hydrogen Economy," a report from the Basic Energy Sciences Workshop (May 2003), http://www.sc.doe.gov/bes/hydrogen.pdf.

[33] European Commission Report "Hydrogen Energy and Fuel Cells". The figure is illustrative and does not represent relative quantities. http://www.ewea.org/documents/12_hlg_summary_vision_report_en.pdf p 3.

essential component of our nation's energy security investment. This investment must also be recognized as an important complement and contributor to the goals of the Hydrogen Initiative. Indeed, hydrogen will require a clean and secure energy source for its production.

It is likely that the early phases of any Hydrogen Economy will rely on production methods that use fossil fuels. As discussed in the Production subsection of this report, the most promising near-term method is natural gas reforming. But, such reforming is operating near theoretical limits and is still several times more expensive than gasoline.[34] However, natural gas reforming is recognized as a viable short-term production method that can be used as a stepping-stone to a Hydrogen Economy. As yet, natural gas reforming is not a clean means of producing hydrogen – carbon dioxide is released in the process. Consequently, limiting overall CO_2 emissions in the early phases of a Hydrogen Economy will come primarily in the form of decreases made through advances in energy efficiency and renewable energy.

As yet, coal gasification is also not a clean means of producing hydrogen. A key research challenge is the capturing and storage – or sequestration – of the CO_2 that is released in the gasification process. The FutureGen program is directing resources at this problem.[35] But again, until an economical solution to the sequestration problem is found, net reductions in overall CO_2 emissions can only come through advances in energy efficiency and renewable energy.

As shown in figure 4, using electricity to separate hydrogen out of water can also produce hydrogen. This electrolysis process can be made to work using any source of electricity including hydropower, wind, solar, and nuclear fission. The current cost to produce hydrogen in this manner is primarily driven by the cost of electricity and is roughly 4 to 10 times more expensive than gasoline. However, the cost of clean electrolysis-production improves directly as power sources - such as wind and solar - become cheaper and more efficient. Therefore, a continued investment in renewable energy is a direct benefit to the goals of the Hydrogen Initiative.

... The Initiative should plan for the possibility that the 2020 timeline may slip.

Since the investments in energy efficiency and renewables benefit the overall goal of energy security and the production goals of the Hydrogen Initiative, the Initiative should not displace research in vital and promising EERE areas.

Some clear planning should be done to address the possibility that the 2020 timeline for commercially viable hydrogen vehicles may slip. In that event, technologies that serve as a so-called "bridge" between the current fossil-fuel economy and any future hydrogen economy will play a bigger role. For example, hybrid gas/electric vehicles are a bridge technology that can "reduce pollution and our dependence on foreign oil until longer-term technologies like hydrogen fuel

[34] Department of Energy, http://fossil.energy.gov/programs/fuels/hydrogen/hydrogen-from-gas.shtml
[35] http://www.fossil.energy.gov/programs/powersystems/futuregen/futuregen_factsheet.pdf

cells are market-ready."[36] The longer it takes for hydrogen vehicles to become competitive, the more the market will need to rely on such bridge technologies.

Research in "bridge" technologies – such as hybrid gas/electric vehicles or internal combustion hydrogen engines – is on going. Honda and Toyota are marketing hybrid cars. Yet, such technologies can benefit from having appropriate recognition in the overall Hydrogen Initiative. An increased focus in the Hydrogen Initiative on relevant basic science and engineering that advances bridge technologies would serve as a sensible hedge to the possibility that the 2020 goal may slip. It would at the same time maintain the development of technologies that show clear short-term promise.

There are promising short-term applications of hydrogen technology to non-transportation sectors as well. Indeed, as shown in figure 4, transportation is only one of a number of possible applications for hydrogen. The Hydrogen Initiative is primarily focused on meeting goals related to the transportation sector. However, it is worthwhile considering whether applications in other sectors, such as stationary fuel cells, are being given adequate attention in the Initiative. Stationary fuel cells have performance requirements that are considerably easier to meet and have greater commercial readiness.

Promising applications in the non-transportation sector that address the Hydrogen Initiative goal of energy security should be considered as essential parallel investments. Advancing alternative applications – such as stationary fuel cells - that show near-term promise provides a complementary strategy that may help advance the automotive application. Alternative applications would greatly benefit from increased emphasis in the Initiative.

Recommendations:

- Promising Federal investments in energy efficiency research and renewable energy research are an important complement and contributor to the goals of a hydrogen economy and should not be displaced by the growth of the Hydrogen Initiative. These investments become increasingly important in the event that the significant technology hurdles for the Initiative are not met within the proposed timeline.
- There should be increased focus in the Hydrogen Initiative on relevant basic science and engineering that advances bridge technologies such as hybrid vehicles & internal-combustion hydrogen engines.
- Congress should evaluate whether hydrogen applications in the non-transportation sector are receiving appropriate attention within the overall Hydrogen Initiative plan.

[36] Steve Chalk, DOE, November 12, 2003, "Leading our Nation to Energy Independence", http://www.chemistry.org/portal/resources/ACS/ACSContent/government/scproject/chalk.pdf

Appendix I: Methodology, Authors and Review Panel

This report has drawn on the knowledge of a broad range of experts. Together, the authors and reviewers have considerable experience in bench science, the management of industrial technology programs from the laboratory to systems level, management of government R&D programs, and the economics of government energy-commercialization programs. In addition, some authors and reviewers have particular expertise in the areas of hydrogen storage, hydrogen production, and fuel cells.

The authors did not carry out a new analysis of the scientific elements of the Hydrogen Initiative. Instead, the authors distilled the considerable scientific analysis presented in the "Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use" and other sources. Further, the authors had complete access to all the material presented to the National Research Council's Committee on Alternatives and Strategies for Future Hydrogen Production and Use. Finally, the authors examined the Hydrogen Energy Roadmap and numerous presentations by government officials managing the Hydrogen Initiative. All of the background information used in this study is referenced in footnotes throughout the report.

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PREPARED STATEMENT OF DR. JOSEPH ROMM

Author, The Hype about Hydrogen *(Island Press, March 2004); Former Acting Assistant Secretary of Energy*

Mr. Chairman and esteemed Members of the Science Committee, I thank you for the opportunity to submit this testimony. I wish to express my appreciation for the strong support this committee has shown for clean energy technology R&D over the course of several decades.

Hydrogen and fuel cell cars are being hyped today as few technologies have ever been. In his January 2003 State of the Union address, President Bush announced a $1.2 billion research initiative, "so that the first car driven by a child born today could be powered by hydrogen, and pollution-free." The April 2003 issue of *Wired* magazine proclaimed, "How Hydrogen can save America." In August 2003, General Motors said that the promise of hydrogen cars justified delaying fuel-efficiency regulations.

Yet, for all the hype, a number of recent studies raise serious doubts about the prospects for hydrogen cars. In February 2004, a prestigious National Academy of Sciences panel concluded, "In the best case scenario, the transition to a hydrogen economy would take many decades, and any reductions in oil imports and carbon dioxide emissions are likely to be minor during the next 25 years." And that's the best case. Realistically, as I discuss in my new book *"The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate,"* a major effort to introduce hydrogen cars before 2030 would undermine efforts to reduce emissions of heat-trapping greenhouse gases like carbon dioxide—the main culprit in last century's planet-wide warming of one degree Fahrenheit.

As someone who helped oversee the Department of Energy's program for clean energy, including hydrogen, for much of the 1990s—during which time we increased hydrogen funding by a factor of ten with the support of the Committee—I believe that continued research into hydrogen remains important because of its potential to provide a pollution-free substitute for oil in the second half of this century. But if we fail to limit greenhouse gas emissions over the next decade—and especially if we fail to do so because we have bought into the hype about hydrogen's near-term prospects—we will be making an unforgivable national blunder that may lock in global warming for the U.S. of one degree Fahrenheit *per decade* by mid-century.

HYDROGEN AND FUEL CELLS

Hydrogen is not a readily accessible energy source like coal or wind. It is bound up tightly in molecules like water and natural gas, so it is expensive and energy-intensive to extract and purify. A hydrogen economy—which describes a time when the economy's primary energy carrier is hydrogen made from sources of energy that have no net emissions of greenhouse gases—rests on two pillars: a pollution-free source for the hydrogen itself and a fuel cell for efficiently converting it into useful energy without generating pollution.

Fuel cells are small, modular, electrochemical devices, similar to batteries, but which can be continuously fueled. For most purposes, you can think of a fuel cell as a "black box" that takes in hydrogen and oxygen and puts out only water plus electricity and heat.

The most promising fuel cell for transportation is the Proton Exchange Membrane (PEM) fuel cell, first developed in the early 1960s by General Electric for the Gemini space program. The price goal for transportation fuel cells is to come close to that of an internal combustion engine, roughly $30 per kilowatt. Current PEM costs are about 100 times greater. It has taken wind power and solar power each about twenty years to see a tenfold decline in prices, after major government and private-sector investments in R&D, and they still each comprise well under one percent of U.S. electricity generation. A major technology breakthrough is needed in transportation fuel cells before they will be practical.

THE STORAGE SHOW-STOPPER?

Running a fuel cell car on pure hydrogen, the option now being pursued most automakers and fuel cell companies, means the car must be able to safely, compactly, and cost-effectively store hydrogen onboard. This is a major technical challenge. At room temperature and pressure, hydrogen takes up some 3,000 times more space than gasoline containing an equivalent amount of energy. The Department of Energy's 2003 *Fuel Cell Report* to Congress notes:

> Hydrogen storage systems need to enable a vehicle to travel 300 to 400 miles and fit in an envelope that does not compromise either passenger space or stor-

age space. Current energy storage technologies are insufficient to gain market acceptance because they do not meet these criteria.

The most mature storage options are liquefied hydrogen and compressed hydrogen gas.

Liquid hydrogen is widely used today for storing and transporting hydrogen. Liquids enjoy considerable advantages over gases from a storage and fueling perspective: They have high energy density, are easier to transport, and are typically easier to handle. Hydrogen, however, is not typical. It becomes a liquid only at -423°F, just a few degrees above absolute zero. It can be stored only in a super-insulated cryogenic tank.

Liquid hydrogen is exceedingly unlikely to be a major part of a hydrogen economy because of the cost and logistical problems in handling liquid hydrogen and because liquefaction is so energy intensive. Some 40 percent of the energy of the hydrogen is required to liquefy it for storage. Liquefying one kg of hydrogen using electricity from the U.S. grid would by itself release some 18 to 21 pounds of carbon dioxide into the atmosphere, roughly equal to the carbon dioxide emitted by burning one gallon of gasoline.

Compressed hydrogen storage is used by nearly all prototype hydrogen vehicles today. Hydrogen is compressed up to pressures of 5,000 pounds per square inch (psi) or even 10,000 psi in a multistage process that requires energy input equal to 10 percent to 15 percent of the hydrogen's usable energy content. For comparison, atmospheric pressure is about 15 psi.

Working at such high pressures creates overall system complexity and requires materials and components that are sophisticated and costly. And even a 10,000-psi tank would take up seven to eight times the volume of an equivalent-energy gasoline tank or perhaps four times the volume for a comparable range (since the fuel cell vehicle will be more fuel efficient than current cars).

The National Academy study concluded that both liquid and compressed storage have "little promise of long-term practicality for light-duty vehicles" and recommended that DOE halt research in both areas. Practical hydrogen storage requires a major technology breakthrough, most likely in solid-state hydrogen storage.

AN UNUSUALLY DANGEROUS FUEL

Hydrogen has some safety advantages over liquid fuels like gasoline. When a gasoline tank leaks or bursts, the gasoline can pool, creating a risk that any spark would start a fire, or it can splatter, posing a great risk of spreading an existing fire. Hydrogen, however, will escape quickly into the atmosphere as a very diffuse gas. Also, hydrogen gas is non-toxic.

Yet, hydrogen has its own major safety issues. It is highly flammable with an ignition energy 20 times smaller than that of natural gas or gasoline. It can be ignited by cell phones and electrical storms located miles away. Hence, leaks pose a significant fire hazard. At the same time, it is one of the most leak-prone of gases. Odorants like sulfur are impractical, in part because they poison fuel cells. Hydrogen burns nearly invisibly, and people have unwittingly stepped into hydrogen flames. Hydrogen can cause many metals, including the carbon steel widely used in gas pipelines, to become brittle. In addition, any high-pressure storage tank presents a risk of rupture. For these reasons, hydrogen is subject to strict and cumbersome codes and standards, especially when used in an enclosed space where a leak might create a growing gas bubble.

Some 22 percent or more of hydrogen accidents are caused by undetected hydrogen leaks. This "despite the special training, standard operating procedures, protective clothing, electronic flame gas detectors provided to the limited number of hydrogen workers," as Russell Moy, former group leader for energy storage programs at Ford Motors has wrote in the November 2003 *Energy Law Journal.* Moy concludes "with this track record, it is difficult to imagine how hydrogen risks can be managed acceptably by the general public when wide-scale deployment of the safety precautions would be costly and public compliance impossible to ensure." Thus, major innovations in safety will be required before a hydrogen economy is practical.

AN EXPENSIVE FUEL

A key problem with the hydrogen economy is that pollution-free sources of hydrogen are unlikely to be practical and affordable for decades. Indeed, even the pollution-generating means of making hydrogen are currently too expensive and too inefficient to substitute for oil.

Natural gas (methane or CH_4) is the source of 95 percent of U.S. hydrogen. The overall energy efficiency of the steam methane reforming process (the ratio of the energy in the hydrogen output to the energy in the natural gas fuel input) is about 70 percent.

According to a comprehensive 2002 analysis for the National Renewable Energy Laboratory by Dale Simbeck and Elaine Chang, the cost of producing and delivering hydrogen from natural gas, or producing hydrogen on-site at a local filling station, is $4 to $5 per kilogram (without adding in any fuel taxes), comparable to a price of gasoline of $4–$5 a gallon (since a kilogram of hydrogen contains about the same usable energy as a gallon of gasoline). This is over three times the current untaxed price of gasoline. Considerable R&D is being focused on efforts to reduce the cost of producing hydrogen from natural gas, but fueling a significant fraction of U.S. cars with hydrogen made from natural gas makes little sense, either economically or environmentally, as discussed below.

Water can be electrolyzed into hydrogen and oxygen. This process is extremely energy-intensive. Typical commercial electrolysis units require about 50 kiloWatt-hours (kWh) per kilogram, an energy efficiency of 70 percent. The cost today of producing and delivering hydrogen from a central electrolysis plant is estimated at $7 to $9 per kilogram. The cost of on-site production at a local filling station is estimated at $12 per kg. Replacing one half of U.S. ground transportation fuels in 2025 (mostly gasoline) with hydrogen from electrolysis would require about *as much electricity as is sold in the U.S. today.*

From the perspective of global warming, electrolysis makes little sense for the foreseeable future. Burning a gallon of gasoline releases about 20 pounds of carbon dioxide. Producing one kg of hydrogen by electrolysis would generate, on average, 70 pounds of carbon dioxide. Hydrogen could be generated from renewable electricity, but that would be even more expensive and, as we will see, renewable electricity has better uses for the next few decades.

Other greenhouse-gas-free means of producing hydrogen are being pursued. The Department of Energy's FutureGen project is aimed at designing, building, and constructing a 270-megawatt prototype coal plant that would co-generate electricity and hydrogen while removing 90 percent of the carbon dioxide. The goal is to validate the viability of the system by 2020. If a permanent storage location can be found for the carbon dioxide, such as an underground reservoir, this would mean that coal could be a virtually carbon-free source of hydrogen. The Department is also pursuing thermochemical hydrogen production systems using nuclear power with the goal of demonstrating commercial scale production by 2015. Biomass (plant matter) can be gasified and converted into hydrogen in a process similar to coal gasification. The cost of delivered hydrogen from gasification of biomass has been estimated at $5 to $6.30 per kg. It is unlikely that any of these approaches could provide large-scale sources of hydrogen at competitive prices until after 2030.

Stranded investment is one of the greatest risks faced by near-term hydrogen production technologies. For instance, if over the next two decades we built a hydrogen infrastructure around small methane reformers in local fueling stations, and then decided that U.S. greenhouse gas emissions must be dramatically reduced, we would have to replace that infrastructure almost entirely. John Heywood, director of the Sloan Automotive Lab at the Massachusetts Institute of Technology, argues, "If the hydrogen does not come from renewable sources, then it is simply not worth doing, environmentally or economically." A major technology breakthrough will be needed to deliver low-cost, zero-carbon hydrogen.

THE CHICKEN-AND-EGG PROBLEM

Bernard Bulkin, Chief Scientist for British Petroleum, discussed BP's experience with its customers at the National Hydrogen Association annual conference in March 2003. He said, "if hydrogen is going to make it in the mass market as a transport fuel, it has to be available in 30 to 50 percent of the retail network from the day the first mass manufactured cars hit the showrooms." Yet, a 2002 analysis by Argonne National Laboratory found that even with improved technology, "the hydrogen delivery infrastructure to serve 40 percent of the light duty fleet is likely to cost over $500 billion." Major breakthroughs in both hydrogen production and delivery will be required to reduce that figure significantly.

Another key issue is the chicken-and-egg problem: Who will spend the hundreds of billions of dollars on a wholly new nationwide infrastructure to provide ready access to hydrogen for consumers with fuel-cell vehicles until millions of hydrogen vehicles are on the road? Yet who will manufacture and market such vehicles until the infrastructure is in place to fuel those vehicles? And will car companies and fuel providers be willing to take this chance before knowing whether the public will embrace these cars? I fervently hope to see an economically, environmentally, and politically plausible scenario for how this classic Catch-22 chasm can be bridged; it does not yet exist.

Centralized production of hydrogen is the ultimate goal. A pure hydrogen economy requires that hydrogen be generated from carbon-dioxide-free sources, which would almost certainly require centralized hydrogen production closer to giant windfarms or at coal/biomass gasification power plants where carbon dioxide is extracted for permanent underground storage. That will require some way of delivering massive quantities of hydrogen to tens of thousands of local fueling stations.

Tanker trucks carrying liquefied hydrogen are commonly used to deliver hydrogen today, but make little sense in a hydrogen economy because of liquefaction's high energy cost. Also, few automakers are pursuing onboard storage with liquid hydrogen. So after delivery, the fueling station would still have to use an energy-intensive pressurization system. This might mean that storage and transport alone would require some 50 percent of the energy in the hydrogen delivered, negating any potential energy and environmental benefits from hydrogen.

Pipelines are also used for delivering hydrogen today. Interstate pipelines are estimated to cost $1 million per mile or more. Yet, we have very little idea today what hydrogen-generation processes will win in the marketplace over the next few decades—or whether hydrogen will be able to successfully compete with future high-efficiency vehicles, perhaps running on other pollution-free fuels. This uncertainty makes it unlikely anyone would commit to spending tens of billions of dollars on hydrogen pipelines before there are very high hydrogen flow rates transported by other means, and before the winners and losers in both the production end and the vehicle end of the marketplace have been determined. In short, pipelines are unlikely to be the main hydrogen transport means until the post-2030 period.

Trailers carrying compressed hydrogen canisters are a flexible means of delivery, but are relatively expensive because hydrogen has such a low energy density. Even with technology advances, a 40-metric-ton truck might deliver only about 400 kg of hydrogen into onsite high-pressure storage. A 2003 study by ABB researchers found that for a delivery distance of 300 miles, the delivery energy approaches 40 percent of the usable energy in the hydrogen delivered. Without dramatic improvement in high-pressure storage systems, this approach seems impractical for large-scale hydrogen delivery.

Producing hydrogen on-site at local fueling stations is the strategy advocated by those who want to deploy hydrogen vehicles in the next two decades. On-site electrolysis is impractical for large-scale use because it would be highly expensive and inefficient, while generating large amounts of greenhouse gases and other pollutants. The hydrogen would need to be generated from small methane reformers. Although onsite methane reforming seems viable for limited demonstrations and pilots, it is also both impractical and unwise for large-scale application, for a number of reasons.

First, the upfront cost is very high—more than $600 billion just to provide hydrogen fuel for 40 percent of the cars on the road, according to Argonne. A reasonable cost estimate for the initial hydrogen infrastructure, derived from Royal Dutch/Shell figures, is $5000 per car.

Second, the cost of the delivered hydrogen itself in this option is also higher than for centralized production. Not only are the small reformers and compressors typically more expensive and less efficient than larger units, but they will likely pay a much higher price for the electricity and gas to run them. A 2002 analysis put the cost at $4.40 per kg (that is, equal to $4.40 per gallon of gasoline).

Third, "the risk of stranded investment is significant, since much of an initial compressed hydrogen station infrastructure could not be converted later if either a non-compression hydrogen storage method or liquid fuels such as a gasoline-ethanol combination proved superior" for fuel-cell vehicles." This was the conclusion of a major 2001 study for the California Fuel-Cell Partnership, a Sacramento-based public-private partnership to help commercialize fuel cells. Most of a methane-based investment would also likely be stranded once the ultimate transition to a pure hydrogen economy was made, since that would almost certainly rely on centralized production and not make use of small methane reformers. Moreover, it's possible the entire investment would be stranded in the scenario where hydrogen cars simply never achieve the combination of popularity, cost, and performance to triumph in the marketplace.

In the California analysis, it takes 10 years for investment in infrastructure to achieve a positive cash flow, and to achieve this result requires a variety of technology advances in both components and manufacturing. Also, even a small tax on hydrogen (to make up the revenue lost from gasoline taxes) appears to delay positive cash flow indefinitely. The high-risk and long-payback nature of this investment would seem far too great for the vast majority of investors, especially given alternative fuel vehicles history.

The U.S. has a great deal of relevant experience in the area of alternative fuel vehicles that is often ignored in discussions about hydrogen. The 1992 Energy Policy Act established the goal of having alternative fuels replace at least 10 percent of petroleum fuels in 2000, and at least 30 percent in 2010. By 1999, some one million alternative fuel vehicles were on the road, only about 0.4 percent of all vehicles. A 2000 General Accounting Office report explained the reasons for the lack of success:

> Fundamental economic impediments—such as *the relatively low price of gasoline, the lack of refueling stations for alternative fuels, and the additional cost to purchase these vehicles*—explain much of why both mandated fleets and the general public are disinclined to acquire alternative fuel vehicles and use alternative fuels.

It seems likely that all three of these problems will hinder hydrogen cars. Compared to other alternative fuels (such as ethanol and natural gas), the best analysis today suggests hydrogen will have a much higher price for the fuel, the fueling stations, and the vehicles.

The fourth reason that producing hydrogen on-site from natural gas at local fueling stations is impractical is that natural gas is simply the wrong fuel on which to build a hydrogen-based transportation system:

- The U.S. consumes nearly 23 trillion cubic feet (tcf) of natural gas today and is projected to consume more than 30 tcf in 2025. Replacing 40 percent of ground transportation fuels with hydrogen in 2025 would probably require an *additional* 10 tcf of gas (plus 300 *billion* kwh of electricity—10 percent of current power usage). Politically, given the firestorm over recent natural gas supply constraints and price spikes, it seems very unlikely the U.S. government and industry would commit to natural gas as a substitute for even a modest fraction of U.S. transportation energy.
- Much if not most incremental U.S. natural gas consumption for transportation would likely come from imported liquefied natural gas (LNG). LNG is dangerous to handle and LNG infrastructure is widely viewed as a likely terrorist target. Yet one of the major arguments in favor of alternative fuels has been their ability to address concerns over security and import dependence.
- Finally, natural gas has too much economic and environmental value to the electric utility, industrial, and buildings sectors to justify diverting significant quantities to the transportation sector, thereby increasing the price for all users. In fact, using natural gas to generate significant quantities of hydrogen for transportation would, for the foreseeable future, undermine efforts to combat global warming (as discussed below).

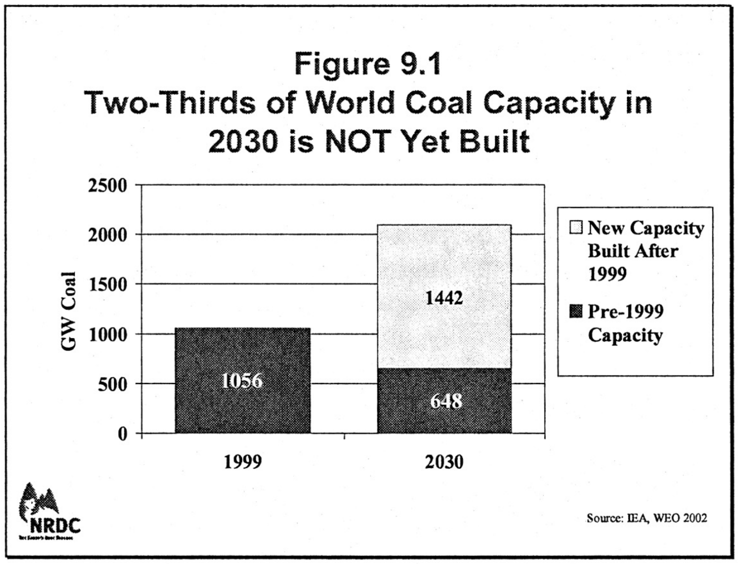
Thus, beyond limited pilot stations, it would be unwise to build thousands of local refueling stations based on steam methane reforming (or, for that matter, based on any technology not easily adaptable to delivery of greenhouse-gas-free hydrogen).

THE GLOBAL WARMING CENTURY

Perhaps the ultimate reason hydrogen cars are a post-2030 technology is the growing threat of global warming. Our energy choices are now inextricably tied to the fate of our global climate. The burning of fossil fuels—oil, gas and coal—emits carbon dioxide (CO_2) into the atmosphere where it builds up, blankets the earth and traps heat, accelerating global warming. We now have greater concentrations of CO_2 in the atmosphere than at any time in the past 420,000 years, and probably anytime in the past three million years—leading to rising global temperatures, more extreme weather events (including floods and droughts), sea level rise, the spread of tropical diseases, and the destruction of crucial habitats, such as coral reefs.

Carbon-emitting products and facilities have a very long lifetime: Cars last 13 to 15 years or more, coal plants can last 50 years. Also, carbon dioxide lingers in the atmosphere trapping heat for more than a century. These two facts together create an urgency to avoid constructing another massive and long-lived generation of energy infrastructure that will cause us to miss the window of opportunity for carbon-free energy until the next century.

Between 2000 and 2030, the International Energy Agency (IEA) projects that coal generation will double. The projected new plants would commit the planet to total carbon dioxide emissions of some 500 billion metric tons over their lifetime, which is roughly half the total emissions from all fossil fuel consumed worldwide during the past 250 years.



Building these coal plants would dramatically increase the chances of catastrophic climate change. What we need to build is carbon-free power. A March 2003 analysis in *Science* magazine by Ken Caldeira et al. concluded that if our climate's sensitivity to greenhouse gas emissions is in the mid-range of current estimates, "stabilization at 4°C warming would require installation of 410 megawatts of carbon emissions-free energy capacity each day" for 50 years. Yet current projections for the next 30 years are that we will build just 80 megawatts per day.

Since planetary warming accelerates over time, and since temperatures over the continental U.S. land mass are projected to rise faster than the average temperature of the planet, a warming of 4°C (over 7°F) means that by mid-century, the U.S. temperature could well be rising as much *per decade* as it rose all last century: one degree Fahrenheit. This scenario, which I am labeling "The Global Warming Century," would be a climate catastrophe—one that the American public is wholly unprepared for.

In February 2003, British Prime Minister endorsed the conclusion of Britain's Royal Commission on Environmental Pollution: "to stop further damage to the climate. . .a 60 percent reduction [in global emissions] by 2050 was essential."

Unfortunately, the path set by the current energy policy of the U.S. and developing world will dramatically *increase* emissions over the next few decades, which will force sharper and more painful reductions in the future when we finally do act. Global CO_2 emissions are projected to rise more than 50 percent by 2030. From 2001 to 2025, the U.S. Energy Information Administration (EIA) projects a 40 percent increase in U.S. coal consumption for electricity generation. And the U.S. transportation sector is projected to generate nearly half of the 40 percent rise in U.S. CO_2 emissions forecast for 2025, which again is long before hydrogen-powered cars could have a positive impact on greenhouse gas emissions.

Two points are clear. First, we cannot wait for hydrogen cars to address global warming. Second, we should not pursue a strategy to reduce greenhouse gas emissions in the transportation sector that would undermine efforts to reduce greenhouse gas emissions in the electric generation sector. Yet that is precisely what a hydrogen-car strategy would do for the next few decades.

HYDROGEN CARS AND GLOBAL WARMING

For near-term deployment, hydrogen would almost certainly be produced from fossil fuels. Yet running a fuel-cell car on such hydrogen in 2020 would offer no significant life-cycle greenhouse gas advantage over the 2004 Prius running on gasoline.

Further, fuel cell vehicles are likely to be much more expensive than other vehicles, and their fuel is likely to be more expensive (and the infrastructure will probably cost hundreds of billions of dollars). While hybrids and clean diesels may cost more than current vehicles, at least when first introduced, their greater efficiency means that, unlike fuel cell vehicles, they will pay for most if not all of that extra upfront cost over the lifetime of the vehicle. A June 2003 analysis in *Science* magazine by David Keith and Alex Farrell put the cost of CO_2 avoided by fuel cells running on zero-carbon hydrogen at more than $250 per ton even with a very optimistic fuel cell cost. An advanced internal combustion engine could reduce CO_2 for far less and possibly for a net savings because of the reduced fuel bill.

Probably the biggest analytical mistake made in most hydrogen studies-including the recent National Academy report—is failing to consider whether the fuels that might be used to make hydrogen (such as natural gas or renewables) could be better used simply to make electricity. For example, the life-cycle or "well-to-wheels" efficiency of a hydrogen car running on gas-derived hydrogen is likely to be under 30 percent for the next two decades. The efficiency of gas-fired power plants is already 55 percent (and likely to be 60 percent or higher in 2020). Co-generation of electricity and heat using natural gas is over 80 percent efficient. And by displacing coal, the natural gas would be displacing a fuel that has much higher carbon emissions per unit energy than gasoline. For these reasons, natural gas is far more cost-effectively used to reduce CO_2 emissions in electric generation than it is in transportation.

The same is true for renewable energy. A megawatt-hour of electricity from renewables like wind power, if used to manufacture hydrogen for use in a future fuel-cell vehicle, would save slightly under 500 pounds of carbon dioxide compared to the best *current* hybrids. That is less than the savings from using the same amount of renewable electricity to displace a future natural gas plant (800 pounds), and far less than the savings from displacing coal power (2200 pounds).

As the June 2003 *Science* analysis concluded: "Until CO_2 emissions from electricity generation are virtually eliminated, it will be far more cost-effective to use new CO_2-neutral electricity (such as wind) to reduce emissions by substituting for fossil-electric generation than to use the new electricity to make hydrogen." Barring a drastic change in U.S. energy policy, our electric grid will not be close to CO_2-free until well past 2030.

A 2004 analysis by Jae Edmonds et al. of Pacific Northwest National Laboratory concluded in that even "in the advanced technology case with a carbon constraint. . .hydrogen doesn't penetrate the transportation sector in a major way until *after 2035*."

CONCLUSION

Hydrogen and fuel-cell vehicles should be viewed as post-2030 technologies. In September 2003, a DOE panel on *Basic Research Needs for the Hydrogen Economy* concluded the gaps between current hydrogen technologies and what is required by the marketplace "cannot be bridged by incremental advances of the present state of the art," but instead require "revolutionary conceptual breakthroughs." In sum, "the only hope of narrowing the gap significantly is a comprehensive, long-range program of innovative, high risk/high payoff basic research." The National Academy came to a similar conclusion.

The DOE should focus its hydrogen R&D budget on exploratory, breakthrough research. Given that there are few potential zero-carbon replacements for oil, the DOE is not spending too much on hydrogen R&D. But given our urgent need for reducing greenhouse gas emissions with clean energy, DOE *is* spending far too little on energy efficiency and renewable energy. If DOE's overall clean energy budget is not increased, however, then it would be bad policy to continue shifting money away from efficiency and renewables toward hydrogen. Any incremental money given to DOE should probably be focused on deploying the cost-effective technologies we have today, to buy us more time for some of the breakthrough research to succeed.

The National Academy panel wrote that "it seems likely that, in the next 10 to 30 years, hydrogen produced in distributed rather than centralized facilities will dominate," and so they recommended increased funding for improving small-scale natural gas reformers and water electrolysis systems. Yet any significant shift toward cars running on distributed hydrogen from natural gas or grid electrolysis would undermine efforts to fight global warming. DOE should not devote any R&D to these technologies. In hydrogen production, DOE should be focused solely on finding a low-cost, zero-carbon source, which will almost certainly be centralized. That probably means we won't begin the hydrogen transition until after 2030 because of the logistical and cost problems associated with a massive hydrogen delivery infrastructure.

But we shouldn't be rushing to deploy hydrogen cars in the next two decades anyway, since not only are several R&D breakthroughs required, we also need a revolution in clean energy that dramatically accelerates the penetration rates of new CO_2-neutral electricity. Hydrogen cars might find limited value replacing diesel engines (for example in buses) in very polluted cities before 2030, but they are unlikely to achieve mass-market commercialization by then. That is why I conclude neither government policy nor business investment should be based on the belief that hydrogen cars will have meaningful commercial success in the near- or medium-term.

The longer we wait to deploy existing clean energy technologies, and the more inefficient, carbon-emitting infrastructure that we lock into place, the more expensive and the more onerous will be the burden on all segments of society when we finally do act. If we fail to act *now* to reduce greenhouse gas emissions—especially if fail to act because we have bought into the hype about hydrogen's near-term prospects—future generations will condemn us because *we* did not act when we had the facts to guide us, and *they* will most likely be living in a world with a much hotter and harsher climate than ours, one that has undergone an irreversible change for the worse.